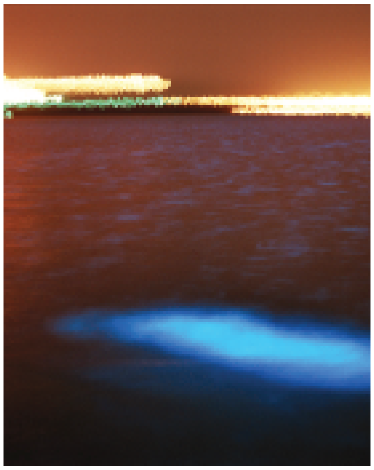
SSC San Diego Biennial Review 2003

3

Intelligence, Surveillance, and Reconnaissance



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Marine Mammal Systems in Support of Force Protection

Robert B. Olds, Jr.
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ABSTRACT

Multiple threat scenarios exist to high-value assets in U.S. ports, including threats from clandestine swimmers, divers, and small underwater vehicles. This paper reviews the Navy's Marine Mammal Program port security and force protection capabilities and how these assets can be used to enhance the ability of security forces to detect and prosecute underwater threats.

INTRODUCTION

This paper reviews the Navy's Marine Mammal Program port security and force protection capabilities and how these assets can be used to enhance the ability of security forces to detect and prosecute underwater threats. The Navy Explosive Ordnance Disposal forces operate and maintain the MK 6 Mod 1 anti-swimmer/diver marine mammal system (MMS). MK 6 is a dolphin-based system that uses Atlantic bottlenose dolphins to detect and mark underwater swimmers and divers in open-water areas such as ship channels and anchorages. SSC San Diego currently maintains a limited capability for demonstrating the Shallow Water Intruder Detection System (SWIDS). SWIDS uses California sea lions to detect and mark underwater intruders in the near-shore areas such as in and around piers.

Recently, dolphins and sea lions were deployed to Submarine Base (SUBASE) Kings Bay for a 30-day MMS port security demonstration. This deployment demonstrated the abilities of the animals to detect and mark a variety of underwater threats and MMS interoperability with the existing SUBASE Kings Bay security force structure. The results of the demonstration were very favorable and clearly demonstrated the ability of the animals to augment and enhance swimmer/diver detection and interdiction at SUBASE Kings Bay. Efforts are currently underway to re-deploy to SUBASE Kings Bay for an extended period to further qualify the value and viability of these systems to serve as a force multiplier for port security operations. Additionally, SWIDS, along with its SSC San Diego team, were most recently tasked to perform force protection and port security operations for naval assets in Bahrain as part of Operation Enduring Freedom.

Multiple threat scenarios exist to high-value assets in U.S. ports, including threats from clandestine swimmers, divers, and small underwater vehicles. This paper discusses the protection of those high-value assets using U.S. Navy MMS assets (MK 6 MMS and SWIDS), which can be applied as physical and waterfront security force protection enhancement assets as shown in Table 1.

TABLE 1. MMS asset security and intruder detection roles.

Task System	Sentry	Patrol/Intruder Response	Other Potential Missions
MK 6 MMS	Yes	Yes. Best suited for open-water patrol and response such as in ship channels and fleet anchorages.	Ship escort Hull searches Pier inspections
SWIDS	No	Yes. Best suited for near-shore areas such as in and around piers and wharves. Also capable of open-water work as described above.	

BACKGROUND

The Navy Marine Mammal Program began in 1959 with independent research programs at China Lake and Point Mugu supported by the Office of Naval Research. The Navy was interested in the hydrodynamics of the dolphin. Broader understanding of how dolphins move in the water was to be applied to improve torpedo, ship, and submarine designs. In 1965, in a program called Sealab II, a dolphin worked for the first time in the open ocean off La Jolla, CA, bringing tools and equipment from the sea surface to divers working 200 feet below. One of the successes of Sealab II was the realization that untethered marine mammals could do useful work in the open sea. The Navy soon realized that there were other open-ocean tasks that would be difficult or potentially hazardous to accomplish using humans or hardware, yet perfectly safe and readily achievable by trained marine mammals.

Sea lions were also found to have useful capabilities and successfully demonstrated the ability to dive and attach missile recovery hardware, allowing for missile retrieval. In 1967, the Advanced Marine Biological Systems (AMBS) program was established as the major research and development component of the Navy's program. The AMBS program explored the capabilities of marine mammals to do Navy tasks. This program also made advances in animal care, health, research, and management of the animals. The AMBS program, along with other acquisition efforts, eventually resulted in the successful introduction of the five MMS currently operational in the Fleet. Supported by fleet MMS, studies continue to further advance our knowledge of marine mammals. This knowledge will be used to enhance current systems and to develop new system capabilities.

OPERATIONAL FLEET SYSTEMS

In its operational fleet systems, the Navy employs dolphins and sea lions to find and mark the location of underwater objects. Dolphins are essential because their exceptional biological sonar is unmatched by hardware sonars in detecting objects in the water column and on the sea floor. Sea lions are used because they have very sensitive underwater directional hearing and low-light-level and turbid-water vision. Both of these marine mammal species are trainable for tasks and are capable of repetitive deep diving. Some of the objects the animals find are expensive to replace. Others could present a danger to Navy personnel, vessels, and facilities. Each MMS is designed for a specific job, but all of the animals work under the care and close supervision of their trainers/handlers. These human/animal teams can be deployed within 72 hours of notice and can be rapidly transported by aircraft, helicopter, and land vehicles with all necessary equipment to potential regional conflict or staging areas all over the world. They regularly participate in major fleet exercises.

Fleet MMS are currently assigned to Navy Explosive Ordnance Disposal Mobile Unit Three (EODMU THREE) and Naval Special Clearance Team ONE (NSCT ONE). Each system has a complement of marine mammals, an officer-in-charge, and several enlisted personnel. The animals are generally trained for a particular operational capability called a "system"; however, animals may be cross-trained to better serve the needs of the Fleet. SSC San Diego supports these fleet systems with replenishment marine mammals, hardware, training, personnel, and documentation.

MK 6 MOD 1 MMS

The MK 6 Mod 1 MMS is a rapidly deployable swimmer detection and marking system that uses dolphins to protect harbors, anchorages, and individual assets against unauthorized swimmers, scuba divers, closed-circuit divers, and swimmer delivery vehicles. The MK 6 Mod 1 MMS is a fielded fleet asset, operated by EODMU THREE, Naval Amphibious Base Coronado. The system was deployed to Vietnam in 1970–71 to protect the ammunition pier at Cam Ranh Bay, and to Bahrain in 1987–88 during Operation Earnest Will. The system is currently tasked in San Diego by the Commander, Navy Region Southwest. SSC San Diego is the life-cycle support activity and performs in-service engineering agent (ISEA), depot, and spares production functions.

MK 6 Mod 1 MMS can be operated in stand-alone mode, or for target reacquisition and marking in response mode following detection by other surveillance systems. Furthermore, the system can be operated as either a roving patrol or a sentry. During patrol operations, a small boat is used to transport personnel, equipment, and a dolphin to the operational site. The dolphin enters the water, and then follows the boat while searching the area, as directed by the trainer, using its biological sonar. If a target (swimmer/diver, swimmer delivery vehicle) is identified, the animal pushes a positive response paddle located on the side of the boat. The dolphin is then given marking hardware, and carries it to the target for marking (Figure 1). For sentry operations, the dolphin is transported to a temporary enclosure that serves as a sentry post. The trainer periodically directs the dolphin to search the vicinity of the post. Following detection and marking, other security assets further prosecute the targets while the dolphin operating team exits the area.

FIGURE 1. MK 6 dolphin marking a scuba diver in open water.

SHALLOW WATER INTRUDER DETECTION SYSTEM

The trainability and reliability of California sea lions has been demonstrated for nearly 30 years by the Navy's MK 5 Mod 1 MMS, which performs the mission of recovering exercise and training mines for the Fleet. California sea lions are very agile and adept at maneuvering in shallow and cluttered waters. They possess extremely good vision in low light and/or high-turbidity areas and excellent directional hearing. These characteristics make these animals uniquely capable in shallow water intruder detection. Biological systems are most useful in areas that cannot make use of fixed sensors because of the physical layout of the area to be protected. California sea lions are easily transported and can be quickly deployed. The capability of sea lions to locate, report, and mark swimmers and scuba divers was initially demonstrated in 1993 during tests at Naval Submarine Bases San Diego, CA, and New London, CT.

Tests of the SWIDS were sponsored by the Defense Nuclear Agency (DNA) in support of the Navy Operational Requirement #214-09-87, Waterside Security Systems (WSS). The capability demonstration was necessitated because WSS performance was degraded in areas around ships, piers, shorelines, and shallow water inlets. Despite a successful demonstration, this capability was never further developed, either as a new system or a product improvement to MK 5 Mod 1 MMS. However, SSC San Diego, which is the Navy Marine Mammal Life-Cycle Support Activity, and performs ISEA, depot, and spares production functions for the MK 5 Mod 1 MMS, maintains a demonstration capability of this potential asset. It can be operated for patrol or clearance in a stand-alone mode, or for target reacquisition and marking in the response mode following detection by other hardware systems or the MK 6 Mod 1 MMS. A small boat is used to transport personnel, equipment, and a sea lion to the operational site. The sea lion enters the water, and searches an area as directed by the trainer (Figure 2). If a target (swimmer/diver) is identified, the animal returns to the boat and pushes a positive response paddle. The sea lion is then given marking hardware and returns for attachment to the leg of the target. The marking hardware is designed to facilitate retrieval and interrogation of the target by other security assets. Other security assets further prosecute marked targets.

In more recent years, the system has drawn force protection interest from the submarine community for security at Trident facilities as well as National Aeronautics and Space Administration (NASA) for coastal protection support during space shuttle launches. SWIDS was most recently tasked with providing force protection and port security for naval assets operating in and around Bahrain.

FIGURE 2. SWIDS searching for intruders in Bahrain.

SUBASE KINGS BAY MMS FORCE PROTECTION DEMONSTRATION

Following the 11 September 2001 terrorist attacks, the requirement to provide enhanced port security and force protection to naval assets has increased significantly. This includes threats from underwater attack. In response to this increased requirement, Office of the Chief of Naval Operations (OPNAV) N775 and Strategic Systems Programs (SSP) co-sponsored an MMS force protection demonstration at SUBASE Kings Bay, GA. The period of this demonstration was from 12 February 2002 to 4 March 2002. The goal of the demonstration was to exhibit the ability of the animals to perform port security duties at Kings Bay as well as investigate the interoperability of these systems to work alongside the existing SUBASE Kings Bay security assets. The deployed assets consisted of two MK 6 Mod 1 dolphins and three SWIDS sea lions along with the required support hardware and personnel. The demonstration was performed in two phases: Phase I focused on data gathering in independent operations; Phase II focused on integrated operations with the established Kings Bay security force structure. MK 6 was tasked to perform sentry and patrol duties, and SWIDS demonstrated patrol and response modes. The opposing force targets consisted of surface swimmers, scuba divers, and closed-circuit divers.

The results of the demonstration were very favorable and clearly demonstrated the ability of the animals to augment and enhance swimmer/diver detection and interdiction at SUBASE Kings Bay. In particular, the capability of the systems to classify targets as actual swimmers/divers and not some other biologic or other false positives is seen as an immediate improvement to the existing underwater detection systems. Additionally, in contrast to other underwater detection systems, the animals provide the added capability of positively responding to a detected underwater threat. Currently, efforts are underway to support an extended deployment of the systems to SUBASE Kings Bay to immediately enhance port security as well as further develop the concept of operations for employing these unique systems both at Kings Bay and other naval bases.

CONCLUSION

The Navy's MMS are a proven asset in force protection and port security. These systems act as an immediate deterrent and can be operated independently or in concert with other security assets. The MK 6 MMS already exists as a fleet system and is currently tasked with performing real-world force protection duties. SWIDS is a demonstrated capability that has shown promising results through each phase of tasking and testing.

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Adaptive Systems Branch Small Mobile Robots

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ABSTRACT

For several years, SSC San Diego's Adaptive Systems Branch has been an important robotic technology developer and supplier to various government agencies and programs, and the Branch now also serves as a centralized resource for the DoD Joint Robotics Program (JRP). This paper describes some of SSC San Diego's leading robotics research and development efforts in the areas of man-portable tactical systems and fixed-installation security systems. The paper also describes some of the ongoing efforts to combine elements of both applications to achieve marsupial delivery capabilities for small unmanned ground and air vehicles hosted by the larger diesel-powered systems.

BACKGROUND

The field of small mobile robots is a relatively new application that, until recently, was not supported by available technology, had very few formally articulated user requirements, and had no significant funding to pursue advanced concepts. While all three conditions have begun to change, the bottom line (and fundamental reason for slow acceptance) is that most users still do not understand the capabilities and/or limits of the technology, and, similarly, technologists do not understand the problems and needs of the user. While there is interest and expectation, few development programs have sufficient personnel and funding to effectively assess the rapidly evolving technology. Late in FY 01, SSC San Diego was designated by the Office of the Secretary of Defense (OSD) as the Center of Excellence for Small Robots for the Joint Robotics Program (JRP) and was tasked with addressing this issue on a global level.

The Center put two fundamental tools in place to serve as closely coupled enabling mechanisms to meet this challenge: (1) the JRP Mobile Robot Knowledge Base (MRKB) and (2) the JRP Small Robot Pool.

MOBILE ROBOT KNOWLEDGE BASE

The JRP Mobile Robot Knowledge Base provides system developers, program managers, and end-users with a centralized online technical resource for unmanned ground vehicles (UGVs). The resource includes information on robot components, subsystems, mission payloads, platforms, and technology transfer opportunities. In addition, the MRKB supports Web-based administration of the Small Mobile Robot Pool asset loan program.

All aspects of the MRKB website and databases are being developed, maintained, and hosted in-house at SSC San Diego. Such capabilities afford maximum control and flexibility to meet the expanding technology needs of the robotics community. The website is logically divided into three sections: (1) Technology Database, (2) Robot Pool, and (3) Technology Transfer. Each section has a similar appearance and navigation menu. All sections provide sponsor information, access to SSC San Diego Robotics Newsletters and the Robot Projects/Publications Website, and additional related links.

SMALL MOBILE ROBOT POOL

While the MRKB seeks to identify and catalog the full spectrum of available component technologies and technology-transfer opportunities that support DoD robotic needs, the effect of this action alone is still overwhelming, given the enormous possibilities. The creation of the JRP Small Mobile Robot Pool was intended to facilitate the link for users with appropriate commercial-off-the-shelf (COTS) solutions by procuring in advance a reasonable selection of hardware deemed most appropriate for subsequent evaluation. The immediate focus in FY 02 was on the basic COTS platforms, while the out-year focus is more toward various application payloads to increase the range of functionality for more value added. By making this pool of hardware easily accessible on a loan basis, prospective users are spared the procurement costs and delays that previously represented a significant hurdle to timely evaluation of effective and reliable hardware.

In addition to having access to manufacturers’ advertised performance specifications, prospective government users will have immediate access to "real-world" user feedback and experiences that can assist them in making the most appropriate selection. The intent is to run at least one version of each different platform through a series of standardized performance evaluations at existing robotic test facilities. As the pool assets are then made available to qualified organizations for evaluation, demonstrations, experiments, and training within the users’ own unique operational domains, the resultant application-specific performance feedback is also collected and made available to other prospective government users. This same feedback is analyzed by SSC San Diego to help prioritize the development of user-requested functionality upgrades in a spiral-development product improvement process.

ONGOING DEVELOPMENT

Man-Portable Robotic System

The Man-Portable Robotic System (MPRS) program goal was to develop lightweight (i.e., user-portable) tactical mobile robots and associated technologies for operation in urban environments. The technical strategy called for optimizing a realistic and robust solution to an appropriate set of articulated requirements by using predominately off-the-shelf components. The MPRS Urban Robot (URBOT) provides users with inspection, surveillance, and reconnaissance capabilities on a platform small enough to be carried into the field by one or two soldiers.

An initial Concept Experiment Program (CEP) was held at Fort Leonard Wood, MO, in 1999 to validate the concept of using small robots to inspect tunnels. The soldiers operating the robots during the CEP represented the Army's 41st Engineer Battalion, 10th Mountain Division, and 577th Engineer Battalion. Based on results from the CEP, four MPRS robots were developed for the Army to evaluate during the Joint Combined Forces (JCF) Advanced Warfighter Experiment (AWE) at Fort Polk, LA, in September 2000. The systems were successfully deployed at the AWE and used during the Military Operations in Urbanized Terrain (MOUT) attack by the Army engineers for forward reconnaissance and tunnel inspection. The MPRS program will help develop the supporting technology required for the Future Combat Systems (FCS) Soldier Unmanned Ground Vehicle (SUGV) program.

URBOT System Description

The URBOT (Figure 1) is a tracked platform 36 inches long, 24 inches wide, 11 inches tall, and weighing 65 pounds. It is completely invertible and watertight, with front, back, top, and bottom video cameras. The high-resolution front inspection camera has zoom, auto-focus, and electronic image stabilization capability. This camera is mounted in a motorized housing that can tilt a full 180 degrees, with two halogen headlights and a microphone. The tilt housing was designed to be a modular unit that could be replaced with other payload packages (i.e., night-vision cameras, thermal cameras, or a small robotic arm and gripper) in an almost plug-and-play manner.

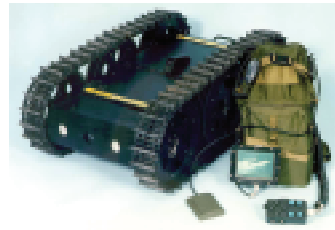


FIGURE 1. MPRS URBOT and wearable OCU.

Autonomous Control

The URBOT is operated via a wearable watertight Operator Control Unit (OCU) (Figure 1 also). A waypoint navigation capability supports the foreseen need for more automation and less reliance on the human operator. This capability allows the operator to send the URBOT through a set of global positioning system (GPS) waypoints selected from an aerial photograph or generated by an outside source, such as another GPS-equipped vehicle (Figure 2). Due to the tactical nature of the URBOTs, this system is also able to operate without the use of a differential GPS master station.

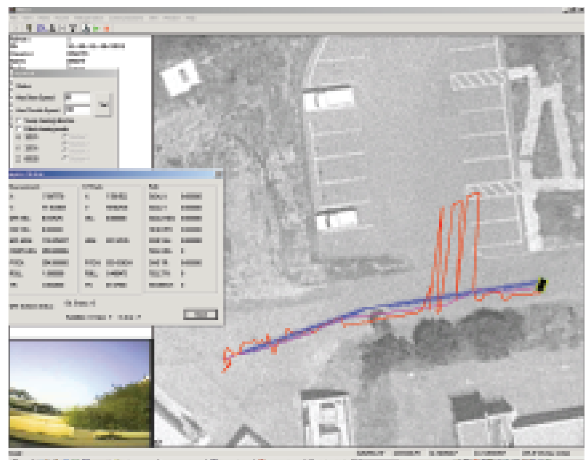


FIGURE 2. Screen shot of MPRS control station for waypoint navigation.

Chemical Sensor Payload

A modular chemical, radiation, and environmental-gas-detection package was also developed and integrated into the URBOT (Figure 3). The chemical payload package allows the robot to carry the same sensors normally used by the warfighter, thus yielding a remote detection capability. The modular package accepts three sensors: the Joint Chemical Agent Detector (JCAD) for chemical warfare agents, the AN-UDR-13 radiation sensor, and the MultiRAE environmental gas sensor. A Limited Objective Experiment (LOE) to test the fundamental concept of employing chemical sensors on a robot was conducted at SSC San Diego in February 2003. In January 2003, the initial payload package had been modified to fit the Mesa Associates, Inc., Matilda robot, and another modification was made in March for the iRobot Packbot. In-theatre demonstrations were conducted in Kuwait in March 2003 to assist in the development of an Operational Needs Statement prior to further production.

FIGURE 3. Chemical payload package on the MPRS URBOT.

Mobile Detection Assessment Response System (MDARS)

The Mobile Detection Assessment Response System (MDARS) is a joint Army–Navy development effort to field mobile robots at DoD sites for physical security and automated inventory missions. There are two types of autonomous platforms: interior to patrol inside warehouses and exterior to patrol the outside of storage facilities. The units carry payloads for intruder detection, inventory assessment, and barrier assessment.

SSC San Diego serves as the MDARS Technical Director and as the Software Developer for the MDARS Control Station. The Control Station is based on the Multiple Resource Host Architecture (MRHA), which allows a single human guard to oversee and monitor up to 255 unmanned platforms and/or sensors. Further development is planned for the MRHA to monitor infrastructure support equipment such as communication relays and to report failures to the guard. The MRHA will automatically control remote doors and gates as needed when an unmanned platform moves into an enclosed area. The MRHA will interface to fixed volumetric sensors that are part of installed (legacy) security systems and will allow the guard to track and display multiple intruders simultaneously by using separate video sources.

Expanded force-protection and force-multiplication capabilities have facilitated investigations into aiming and firing less-than-lethal weapons on the MDARS-Exterior platform as pre-planned product improvement (P3I) efforts (Figure 4). An integrated Marsupial Delivery System was developed to carry and transport smaller deployable assets, such as an MPRS URBOT and/or unmanned air vehicle (UAV) or unmanned ground vehicle (UGV) as shown in Figure 5.

FIGURE 4. MDARS-E prototype platform with gunpod.

FIGURE 5. MDARS-E prototype platform with Marsupial UGV carrier and UAV launch fixture.

Tactical Mobile Robot (TMR) Technology Transfer

The Tactical Mobile Robot (TMR) program, sponsored by the Defense Advanced Research Projects Agency (DARPA), was transitioned to SSC San Diego at the end of FY 02, and provides a convenient enabling mechanism for technology transfer into ongoing JRP-funded development efforts. SSC San Diego works with a variety of DARPA contractors to extract relevant aspects of their research and transfer the technology to related projects such as MDARS, MPRS, and the Small Mobile Robot Pool. Additionally, a number of agreements are in place or pending with other government research activities (i.e., the Jet Propulsion Laboratory [JPL]; the Idaho National Engineering and Environmental Laboratory [INEEL]; the Research, Development, and Engineering Command [RDECOM]; and the Aerospace Robotics Laboratory [ARL]) to foster emergent technology-transfer opportunities. An interior and an exterior research testbed are employed at SSC San Diego to support this process as further discussed below.

Interior Technology-Transition Testbed

A third-generation prototype, Robart III (Figure 6) is an advanced demonstration platform for nonlethal tactical response. This prototype extends the concepts of reflexive teleoperation into the realm of coordinated weapons control (i.e., sensor-aided control of mobility, camera, and weapon functions). Under the TMR Technology Transfer Program, the emphasis is now on the integration of obstacle detection/obstacle avoidance (OD/OA) algorithms optimized for small robotic platforms. Technology-transfer collaboration is initially proceeding with JPL to integrate its arc-based free-space reflexive OD/OA software, with follow-on efforts planned to incorporate the Carnegie Mellon robot navigation toolkit (CARMEN) world-modeling software for unexplored interior structures.

FIGURE 6. Interior technology-transition platform, Robart III.

Exterior Technology-Transition Testbed

For outdoor applications such as MDARS-E and MPRS, the current transition testbed is an iRobot All Terrain Robotic Vehicle (ATRV)

(Figure 7). This unit is equipped with a GPS waypoint navigation package and controlled by the Multiple-robot Operator Control Unit (MOCU), both developed at SSC San Diego. In February 2003, this technology was transitioned to INEEL in exchange for its OD/OA software. One of the first applications for this combined package running on the ATRV will be in support of the upcoming Advanced Robotic Behavior Technology (ARBT) Science and Technology Objective (STO) demonstration in November 2003.

FIGURE 7. Exterior transition platform, iRobot ATRV.

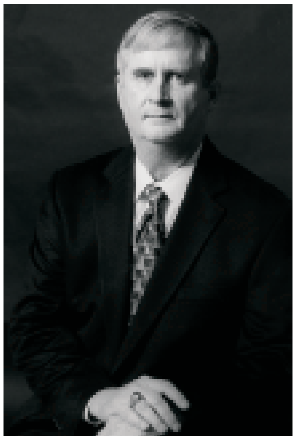
Organic Air Vehicle Mission System

The main project goal is to develop a system that allows a UAV to be launched, recovered, and refueled by a host platform in order to provide force extension through autonomous aerial response. Some of the near-term UAV missions include reconnaissance, radio frequency (RF) communications relays, overhead visual GPS augmentation, surveillance, psychological operations, and mine detection. Future uses include target designation and payload dispersal (i.e., submunitions). Other benefits are seen in the mission flexibility that allows the UAV to be launched from one type of system and recovered by another (e.g., launch from an unmanned surface vehicle and recovered by a UGV). Another benefit is the reduction in time and personnel required to refuel a UAV during mission operations, which thus increases the number of missions a UAV can complete in a given period of time.

FIGURE 8. MDARS-E vehicle with launch fixture for the 29-inch iStar OAV.

SSC San Diego has worked closely with Allied Aerospace, Inc., to develop an initial feasibility demonstration system. A prototype launch fixture was mounted on the MDARS-E vehicle and tested with Allied's 29-inch iSTAR organic air vehicle (OAV) in March 2002 (Figure 8). Design and initial integration of the recover mechanism has been completed, awaiting the integration with MOCU for recovery control. Engineers at SSC San Diego will expand on and prototype the initial design and model of the refueling system developed by mechanical engineering students at the University of California, San Diego.

Projected users include the Cooperative Unmanned Ground Attack Robot (COUGAR) program, the DARPA Perception for Off-road Robots (PerceptOR) program, Naval Special Warfare Group 3, and the Counter Mine Science and Technology Objective (CM STO). Opportunities for collaboration with other government agencies and publication of lessons learned and design processes will also be pursued as part of this project.



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Buoy-Mounted Bioluminescence Sensor (BioBuoy) for Special Operations

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ABSTRACT

BioBuoy is the first autonomous platform that measures bioluminescence, seawater clarity, and temperature for special operations planning. The sensor package consists of a photomultiplier tube for measuring bioluminescence, a transmissometer for measuring water clarity, and a temperature thermistor for measuring temperature. To address the current limitations on making long-term measurements, we recently modified a buoy-mounted oil spill sensor to house a bioluminescence sensor and a transmissometer. Data were collected approximately twice an hour, 24 hours per day, and transmitted by a spread spectrum (900 MHz) radio frequency link to a lab-based computer, and then posted to a secure Internet browser site. The BioBuoy is currently providing, for the first time, autonomous real-time bioluminescence data, which are critical for modeling and predicting bioluminescence in a variety of applications.

INTRODUCTION

While many oceanographic studies have focused on the distribution of bioluminescence in the marine environment, there is still little understanding of its seasonal characteristics [1, 2, and 3]. Previous studies were severely limited in duration as well as in methods to quantify bioluminescence [4, 5, and 6]. Only a few studies have measured bioluminescence on an extended basis, and these were short in duration, usually less than 1 or 2 years with long intervals between sets of measurements [5, 6, and 7]. Others reported data collected at different times of the year but did not address the seasonality of bioluminescence [8]. The lack of long-term studies leaves unanswered important questions regarding the role of bioluminescence in succession phenomena [9].

BioBuoy is the first autonomous platform that measures bioluminescence, seawater clarity, and temperature for Commander, Naval Special Warfare Command operations planning. The sensor package consists of a photomultiplier tube (PMT) for measuring bioluminescence, a transmissometer for measuring water clarity, and a temperature thermistor for measuring temperature. Measurements must be conducted on a continual basis to evaluate seasonal variability to adequately understand and predict ocean bioluminescence. Bioluminescence may impact special operations at night in coastal areas. For example, a diver's swimming motion in the water stimulates hundreds of thousands of cells of bioluminescent microorganisms (dinoflagellates) to emit a visible blue-green light (Figure 1). To address the current limitations on making long-term measurements for operations planning, we modified a buoy-mounted oil spill sensor to house a bioluminescence sensor, a transmissometer, and temperature probe [10]. Data are collected every hour, 24 hours per day, and transmitted by spread spectrum (900 MHz) radio frequency (RF) link to a nearby base station computer or by an ORBCOMM satellite transmitter on the buoy. The ORBCOMM system can transmit buoy data from anywhere in the world on a daily basis. Data are received at SSC San Diego and at the Warfighting Support Center (WSC) at the U.S. Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, MS, where the final product, a tactical decision aid, is generated and posted on a secret Internet protocol router network (SIPRNET) website for use by the Mission Support Center (MSC) at the U.S. Naval Amphibious Base, Coronado, CA. BioBuoy is currently providing, for the first time, autonomous real-time bioluminescence, seawater clarity, and seawater temperature from San Diego Bay and the Persian Gulf.

METHODS

SSC San Diego has developed an automated oil spill sensing technology to provide early notification of the presence of a petroleum spill on water. The fluorescence-based sensor operates from just below the water's surface and is continuously measuring for an increased concentration of hydrocarbons or a surface sheen, which is indicative of an oil spill. When a spill is detected, the data are immediately transmitted to another computer base station for analysis, display, and telephonic alarming. Ultraviolet (UV) fluorescence provides a sensitive means of detecting petroleum hydrocarbons in water. When UV light excites petroleum, the aromatic constituents like benzene and naphthalene emit fluorescence at longer wavelengths. The greater the fluorescence, the higher the concentration of hydrocarbons present. The sensor is an upward-looking multispectral underwater flourometer.

FIGURE 1. A diver's swimming motion several feet below the water's surface stimulates hundreds of thousands of cells of the bioluminescent dinoflagellate *Pyrodinium bahamense* to emit a visible blue-green light in a bioluminescent bay in Vieques, Puerto Rico. (Photo by Frank Borges LLosa, www.frankly.com.)

Multiple ports in the buoy permit water and any potential oil slick to flow unimpeded past the sensor window. The excitation source is a pulsed xenon flash lamp operating at 10 watts average electrical power. Fluorescence resulting from the presence of petroleum hydrocarbons is collected back through an optical window and passed through a series of dichroic filters for separation into three spectral bands. Since different classes of petroleum products fluoresce at different characteristic wavelengths, multispectral analysis provides a means to discriminate between various classes of oils and fuels. It also allows for discrimination between petroleum and non-petroleum (e.g., chlorophyll) fluorescence.

Bioluminescence-Water Clarity Sensors

The bioluminescence system consists of a 1-inch-diameter Hamamatsu photomultiplier tube (PMT) viewing a light-tight darkened 25-mL volume chamber. Seawater is continuously pulled into the chamber by an electric pump at a constant rate of 0.25 L/sec. The turbulence associated with seawater mixing in the chamber stimulates bioluminescent plankton (single-cell dinoflagellates) to emit light within the darkened chamber in front of the PMT. At these flow rates, small bioluminescent zooplankton are also sampled and contribute to the overall bioluminescent signal. A SeaTech red transmissometer (680 nm) is also mounted on the BioBuoy and provides water clarity measurements. In coastal environments, water clarity or percent transmission (%T) is distinctly lower than in the open ocean where seawater is much clearer and can provide information on the regions where microscopic plankton and debris are concentrated. In this system, bioluminescence and %T are programmed to measure these optical properties every one-half hour. Sequentially, the PMT is powered up for 4 seconds before the pump is activated for 10 seconds. During the 10-second sampling period, bioluminescence is quantified and averaged. As the pump is reactivated, %T is measured. The raw data are then sent via the RF link to a home base computer logging the data via a secure net address. Data are processed automatically and posted to a real-time http address. Data are logged into a time series graph and posted to a data file for offloading.

Evolution of BioBuoy

Several variations of BioBuoy have emerged during the past 2 years. The first version, BioBuoy 1 (Figure 2), contained a PMT and transmissometer, and temperature sensor. Figure 3 shows data collected during a rainy period in San Diego Bay in February 2002; bioluminescence and transmission were measured continuously for 1 week. Bioluminescence has a distinct diurnal pattern when measured 24 hours per day. Maximum bioluminescence is nearly always observed midway into the dark hours, while minimum bioluminescence is always observed near mid-day. The onset of rain produces land runoff into the bay and reduces water clarity as indicated by a reduction in transmission. Versions of BioBuoy 1 have been providing continuous data from San Diego Bay at the Explosive Ordnance Disposal Mobile Unit facility and in Bahrain Harbor. Figure 4 shows bioluminescence data for 1 month in San Diego Bay. Buoys have been positioned at the Port Security Unit, the main pier at Mina Salman, and alongside other channel buoys within the harbor. BioBuoy 2, a variant of BioBuoy 1, has distinct modifications (Figure 5). The buoy is alkaline battery powered (not solar panel powered) and data are communicated solely by an ORBCOMM satellite transmitter. On the existing battery pack, BioBuoy 2 will be able to conduct measurements each hour for 2 months and transmit the data every 12 hours to a passing overhead satellite. Data are sent via email in the form of a GlobalGram to a number of users. Data are then decoded by the email recipients and used in the visual detection ratio (VDR) algorithm at NAVOCEANO. The algorithm product is posted on a SIPRNET website for access by the MSC at the U.S. Naval Amphibious Base, Coronado.

Special operations require up-to-date environmental data for planning. Climatology databases are usually historical and have limited value. The BioBuoy provides daily updates for 96-hour planning cycles. Furthermore, real-time data can be used to construct seasonal databases in areas where no data exist. The product, a VDR, aids planners for insertion of special operations forces into designated theaters.

FIGURE 2. BioBuoy 1.

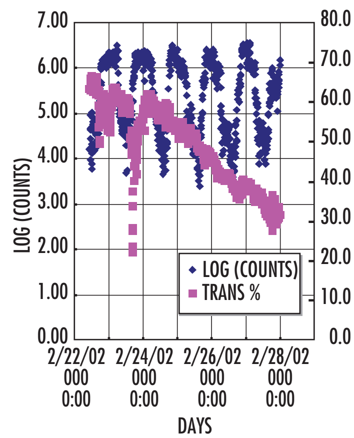

FIGURE 3. BioBuoy 1 bioluminescence and seawater clarity measurements, San Diego Bay, 22–29 February 2000.

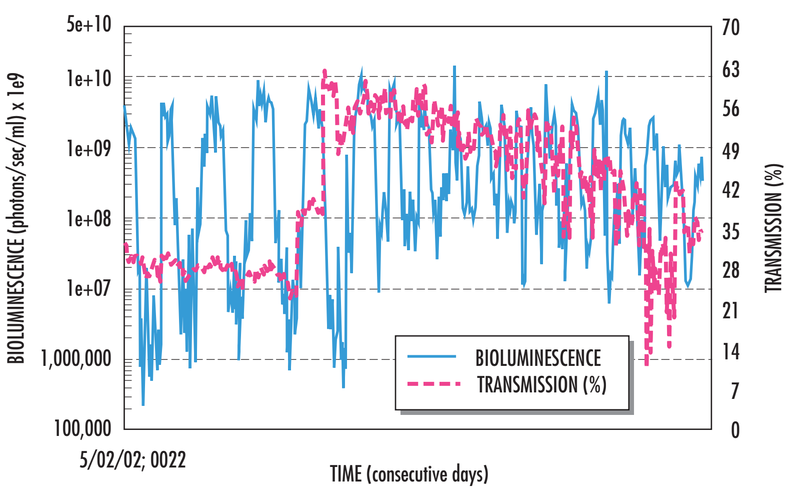

FIGURE 4. BioBuoy 1 bioluminescence data, San Diego Bay, 2±29 May 2002.

FIGURE 5. BioBuoy 2.

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Adapting Imagery and Mission Planning Systems in Support of Enduring Freedom

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ABSTRACT

Operation Enduring Freedom established the need for several high-priority, specialized, rapid response engineering efforts to meet emerging operational requirements in support of the war effort stateside and in the operational area. This paper focuses on five specific development efforts to address imagery, intelligence, mission planning, and targeting requirements. It discusses the efforts to develop existing capabilities using emerging commercial off-the-shelf technologies and rapid engineering prototyping to respond to changing world environments and events.

INTRODUCTION

Operation Enduring Freedom established the need for several high priority, specialized, rapid response engineering efforts to meet emerging operational requirements in support of the war effort both stateside and in the operational area. Requirements came primarily from operationally deployed forces trying to solve immediate real-world problems. Specifications of the requirements were typically sketchy and dealt primarily with the operational outcome not the implementation strategy. This paper describes five specific development efforts by SSC San Diego C^4I Programs Office Philadelphia to address imagery, intelligence, mission planning, and targeting requirements.

The C^4I Programs Office Philadelphia engineering staff was called on to resourcefully use existing technologies and commercially available components to meet the challenges established by the end-users. Responses were always needed within short time windows, forcing quick decisions and often requiring adjustments to design concepts because desired components were not always readily available in the required time frame.

The perception exists that the employment of commercial-off-the-shelf (COTS) hardware and software means that there is no longer an engineering problem to solve in designing and developing a technical solution to a real-world military problem. To the contrary, COTS hardware and software provide the engineer with building blocks to use in assembling an engineering solution to a technical problem.

The issues that need to be addressed focus largely on selecting the appropriate components for compatibility and right-sizing a solution to solve the problem. Knowledge and understanding of the intended operational environment is critical in selecting appropriate equipment and the design packaging.

Frequent interaction between the C^4I Programs Office Philadelphia and vendor engineers have allowed our engineering teams to influence the evolutionary design of Sun workstations and redundant array of inexpensive disks (RAID) arrays, Ciprico RAID arrays, ETI Universal Power Supplies, and Tadpole UNIX® notebooks. Vendors often request that our engineers act as beta testers to ensure that their next-generation products provide the capabilities and functionality needed to meet the military's operational requirements and define and develop technical solutions.

DEVELOPMENT EFFORTS

Downsized Image Product Library (IPL) for Marine Units

The 26th Marine Expeditionary Unit (MEU) required a small portable system to allow them to retrieve, store, catalog, and exploit national imagery and to add tactical imagery to a small library storage unit. The device needed to be compact, lightweight, and rugged, with full Image Product Library (IPL) functionality, and to be capable of serving as an exploitation workstation.

To meet this requirement, a prototype IPL system was developed on a COTS UNIX notebook (Figure 1). The unit architecture was designed to meet Marine requirements for a lightweight downsized IPL, capable of operating within the shipboard local-area network architecture to receive imagery and then to forward-deploy with the Marine unit in the-ater. The COTS software environment was devel-oped and tested on the unit to ensure that all system functionality was preserved in the new architecture and that the unit met operational requirements. A team from the C4I Programs Office Philadelphia, the National Imagery and Mapping Agency (NIMA), and Marine Headquarters met the 26th MEU personnel onboard USS *Iwo Jima* (LHD 7) to deliver the notebook IPL, discuss connectivity and training strategies, and provide technical support in integrating the IPL into the shipboard local-area network. The Marines were pleased to receive the downsized IPL prior to their deployment. They will take the unit into theater, evaluate the product under operational conditions, and provide feedback to be incorporated into the next generation of the system.

FIGURE 1. Tactical Exploitation Library developed for the 26th MEU deploying on USS *Iwo Jima* (LHD 7).

Special Forces Enhanced IPL

The NIMA crisis response team received several operational crisis requirements from Special Forces units who needed tailored IPL systems. The C4I Programs Office Philadelphia was tasked by NIMA to provide the technical response to these specialized requirements.

The Special Operations requirements were met by adapting standard IPL systems (Figure 2) to meet the operational needs for the Special Forces units. IPL version 2.5.1 servers were configured for the 16th Special Operations Wing, Hulburt Field, FL; the 3rd Special Forces Group, Fort Bragg, NC; and the 19th Special Forces Group, Draper, UT. Additional requirements from the units included special hardware and software packages that were incorporated into the basic design of the IPL hard-ware and software. Compact rewritable disks (CD-RWs) and personal computer (PC) co-processors were added to provide a data exchange mechanism and to reduce the number of hardware suites that the unit required for deployment. Additional software packages integrated into the IPL software environment included ERDAS Imagine®, MATRIX, and DataMaster, which provide imagery viewing and exploitation tools, and K-PAR archiving software, which supports compact disk (CD) cre-ation within the UNIX environment and Windows®/Office 2000. These

FIGURE 2. Enhanced Image Product Library for Special Forces units.

COTS items were procured, installed, and tested for operational compatibility prior to system delivery. The first system was deployed within 36 hours after receiving tasking.

In-Theater Replication of Geospatial Intelligence Library

To provide ready access to geospatial information, the U.S. Central Command established a requirement for regional access to a Geospatial Intelligence Library (GIL) that could be queried in the operational theater even when communications to stateside libraries were restricted. The NIMA crisis response team received the requirement and determined that the most expeditious approach to meeting the requirement was to adapt an IPL system to meet the throughput and storage requirements for the system. The C4I Programs Office Philadelphia was tasked by NIMA to provide the hardware technical response to these specialized requirements.

A site survey performed at the U.S. Central Command Theater designated command helped to determine the operational environment and the physical and operational constraints for the system. An upsized COTS hardware platform was selected to meet the storage and processing throughput requirements (Figure 3). The hardware and commercial software were rapidly procured and configured by the engineering team to support standard IPL operations in the redesigned hardware environment. A team of representatives from BAE Systems, NIMA, and the C4I Programs Office Philadelphia convened at the NIMA St. Louis location to complete the preparation of the system prior to deployment into the operational area. While there, the team added specialized software to the system, migrated data, and tested data replication capabilities between the existing NIMA library and the new GIL. C4I Programs Office Philadelphia and BAE Systems personnel installed the system in theater, integrated it into the site's network, and fully tested it in the operational environment. Work is in progress to expand the capabilities of the system and its storage.

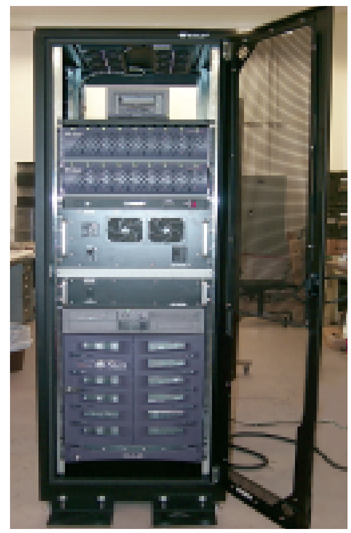

FIGURE 3. Geospatial Intelligence Library for U.S. Central Command theater operations.

Portable Workstation for Tactical Reconnaissance Support

To improve the situational awareness of U.S. Army Green Berets on the ground, the C4I Programs Office Philadelphia personnel, who support Naval Air Systems Command (NAVAIR) PMA-241, teamed with the Army to establish connectivity between Army Special Forces and Navy tactical aircraft for the exchange of imagery and intelligence. An F-14 aviator from Carrier Air Group 7, on a 1-month assignment with an Army intelligence center, identified the need for such a capability when he saw how slowly the imagery intelligence was being delivered to the Special Forces group.

The solution used a customized Fast Tactical Imagery (FTI) portable workstation to enable F-14 crews to transmit and receive imagery from Army Green Berets in Afghanistan (Figure 4). The workstation was programmed to process near-real-time imagery (embedded with coordinate and target information). It was modified to establish an interface capability to the Army PSC-5 radio to receive imagery.

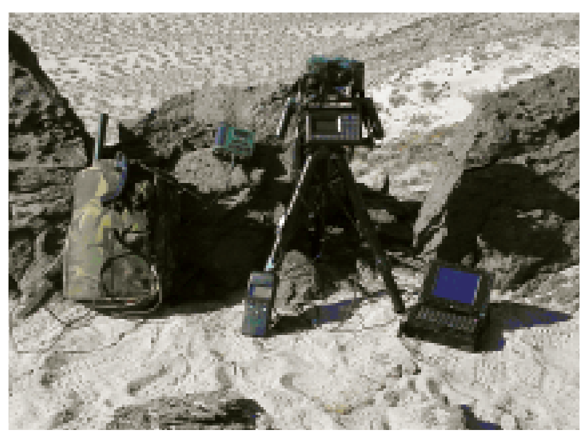

FIGURE 4. Portable Fast Tactical Imagery Workstation (right) with Army radio, navigation, and imagery equipment.

This new capability enables the Green Berets to receive video from the Navy Tactical Air Reconnaissance Pod System-Completely Digital (TARPS-CD) pod, which provides electro-optical capability. Using the modified FTI workstation, the Special Forces were then able to use infrared imagery from the Low-Altitude Navigation and Targeting Infrared for Night (LANTIRN) system, along with electro-optical imagery from TARPS-CD. The FTI workstation is also compatible with the Army's AH-64 Apache helicopter. The new capability gave operational forces the ability to significantly shorten the "sensor-to-shooter" time frame in prosecuting pop-up or mobile targets.

Precision Targeting Workstation for P-3 Aircraft

Naval Air Systems Command (NAVAIR) PMA-281 fields the Precision Targeting Workstation (PTW) as a component of the Joint Service Imagery Processing System–Navy (JSIPS–N) installed on carriers and large-deck amphibious ships. The PTW develops a very precise aim point for engagement of precision-guided munitions based on target registration from national imagery. The problem posed by the operational planners after the Persian Gulf War was how to find, identify, and attack moving targets, such as mobile missile systems, within a narrow time window. NAVAIR believed that their shipboard PTW could be adapted to accomplish part of this task from a P-3 aircraft.

The C^4I Programs Office Philadelphia was tasked to provide a prototype system capable of performing the same functions as the shipboard system but with an architecture designed for a P-3 aircraft. The selected processor was a Sun E420R server with A1000 RAID arrays. This unit is a smaller, lighter server than the E4500 and Ciprico RAID arrays used onboard ship. The system was packaged to withstand the vibration and power environment of an operational P-3 aircraft. The weight distribution of the equipment was also critical in the installation process.

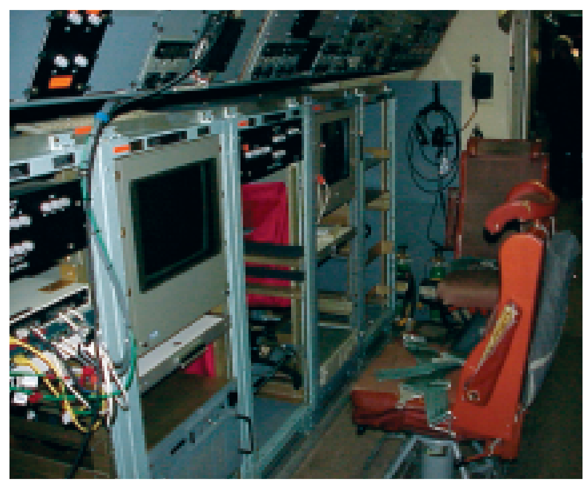

FIGURE 5. First phase of PTW installation on P-3 aircraft.

The system was first installed and tested on a P-3 aircraft during Fleet Battle Experiment India (Figure 5). Incorporated with other system enhancements into the aircraft, the new capabilities allowed the P-3 to transmit high-quality imagery and brief messages with target coordinates to Navy and Air Force aircraft and an Army ground station, demonstrating that target sensing to weapons launch time could be reduced to approximately 10 minutes. This capability promises to greatly enhance situational responsiveness when it is operationally deployed.

CONCLUSION

This paper highlighted some of the engineering efforts necessary to develop existing capabilities using rapid engineering prototyping and commercially available technologies to respond to changing world environments and events.

ACKNOWLEDGMENTS

The author would like to thank the many individuals who contributed to the development and deployment of these specialized systems. Their dedication, commitment, and creativity enabled SSC San Diego C⁴I Programs Office Philadelphia to rapidly resolve real-world problems and provide quality systems to operationally deployed forces. In particular, the engineering talents of Robert Mullen, Norbert Reis, Steven Hoshowsky, Mark Cunningham, and Charles Urbanski were instrumental in making these high-priority, specialized, rapid response systems available to meet the needs of our warfighters.

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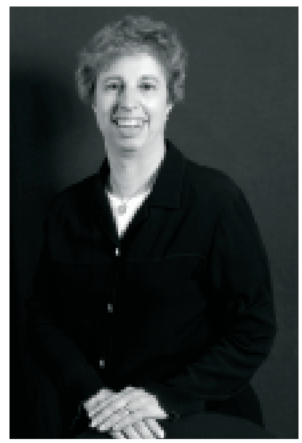

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The eXtensible Tactical C4I Framework (XTCF)

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ABSTRACT

This paper describes a development project for the Office of Naval Research (ONR) to provide a new framework for integrating current and emerging tactical data sources seamlessly. The eXtensible Tactical Command, Control, Communications, Computers, and Intelligence (C^4I) Framework (XTCF) will transform software development in the next generation of command and control tactical data management services. XTCF will provide a common information management framework that will enable multiple data sources, transformation services, analysis tools, and data management services to cooperate in producing a common tactical information network service.

BACKGROUND

The Department of Defense has embarked on a major effort to transform the management of information to enhance operational decision-making, improve combat operations, and realize intelligence advantages. This new, net-centric approach will incorporate network and communications enhancements to support operational users at all levels. A key aspect is making reliable data equally available to users at all levels, from headquarters to the "edge" of the network.

The current approach to command and control of operational forces is based on using the Common Operating Environment (COE) to provide a set of common services and adding mission-specific applications. The Global Command and Control System (GCCS), which is the present Joint command and control (C^2) system, allows Operational Commanders to maintain dominant battlefield awareness through a fused, near-real-time picture of the battlespace. GCCS provides Operational Commanders with integrated imagery and intelligence, situational awareness, indications and warnings, collaborative planning, course-of-action development, and intelligence mission support. GCCS consists of hardware, software, procedures, standards, and interfaces for connectivity worldwide at all levels of command, and it supports and integrates a wide assortment of mission-critical, joint, service, and site-unique applications, databases, and office-automation tools.

A key capability in GCCS is the Tactical Management System (TMS). TMS is the tactical database management and correlation engine for COE-based systems including GCCS, the Maritime variant (GCCS–M), the Army variant (GCCS–A) and Intelligence Analysis System (IAS), and the Air Force Theater Battle Management Core Systems (TBMCS). TMS facilitates the ability of command and control systems to receive, display, correlate, fuse, and maintain locational information on friendly, hostile, and neutral land, sea, and air forces and integrate it with available intelligence and environmental information.

The current TMS implementation is based on a client–server architecture that provides data replication and synchronization services across a multi-layered network distribution topology. The TMS database consists of a large number of pre-defined track types, each with rules for correlation, association, and data field promotion. TMS also serves as a tactical event notifier that allows mission applications to register for and receive track update, change, merge, and delete events in order to provide operational users with a current tactical track picture.

XTCF OBJECTIVES (A TRANSFORMATIONAL APPROACH)

The eXtensible Tactical Command, Control, Communications, Computers, and Intelligence (C^4I) Framework (XTCF) will transform software development in the next generation of command and control tactical data management services. XTCF is providing a Service Oriented Architecture (SOA) to field new data management, correlation, and visualization tools rapidly in a dynamic warfare environment. XTCF will be open and extensible for "plug-in" capabilities that can perform tactical management functions with current and future (i.e., not yet developed or operational) data types and sources. XTCF accomplishes the following objectives:

- Establish a data management framework that enables the integration of new data sources in an operationally relevant timeframe without extensive re-engineering.
- Leverage the data management framework to assist in developing new solutions for existing and new common picture data sources. These solutions will provide both plug-in data representations and plug-in correlation mechanisms for a multi-source picture.
- Improve situational awareness by removing the current limit on the number of tracks and reports and by providing access to larger track histories.

These objectives facilitate integration of intelligence, surveillance, and reconnaissance (ISR) data sources such as signals intelligence (SIGINT), electronic intelligence (ELINT), imagery intelligence (IMINT), measurement and signature intelligence (MASINT), acoustic intelligence (ACINT), tactical digital information link (TADIL or "Link"), and moving-target indicator (MTI) into the common picture without extensive re-engineering. This new, open, and extensible architecture is interoperable with current fielded systems and will provide a framework for integrating current and emerging tactical data sources seamlessly.

Additionally, XTCF will accomplish these objectives by providing a common information management framework that will enable multiple data sources, transformation services, analysis tools, and data management services to cooperate in producing a common tactical information network service. The framework will include the ability to install and activate at runtime new data sources, new data storage agents, new correlation services, new information distribution services, new information query services, and other value-added services. XTCF incorporates these services and tools into the framework as plug-ins. A plug-in may be a group of software components or a single software component. The framework allows new data source developers to take advantage of an existing infrastructure and concentrate on the software that is specific to their applications.

PROJECT SCOPE

XTCF is a development project for the Office of Naval Research (ONR) as part of the Knowledge Superiority and Assurance (KSA) Future Naval Capability (FNC). The XTCF Technology Transition Agreement between the Navy Global Command and Control Systems–Maritime (GCCS–M) Program Office (PMW-157) and ONR states that the "XTCF project will deliver a data management framework that enables more rapid and timely technical and developmental exploitation of emerging complex and heterogeneous data sources for the next-generation common picture." XTCF will permit seamless integration of current and new data sources into the common picture without the extensive re-engineering required today. Using XTCF and associated plug-ins will enhance command and control performance within tactical scenarios such as:

- Combat identification and tracking in a dynamic air-warfare battle problem using visual, radar, and SIGINT data sources in an integrated data management and display environment.
- Time-critical land-attack targeting using MTI, SIGINT, IMINT, and MASINT to provide an integrated picture.
- Increased tactical-data throughput using the evolving Integrated Broadcast Service (IBS), the Tactical Data Information Exchange System-B (TADIXS-B), and enhanced data storage capacity.
- Incorporation of existing SIGINT analysis tools such as the Generic Area Limitation Environment (GALE)-Lite or the Analyst Support Architecture (ASA) that are developed primarily to support sensor signal processing.
- Distributed access to tactical repositories formerly restricted to a local area network (LAN) environment.

Three-Tier Information Architecture

The XTCF software architecture supports a three-tier tactical information model. Tactical information can enter the system as a report, a track, or an entity. A report can consist of parametric measurements (such as those in a typical ELINT report) combined with location measurements (such as an area of uncertainty or line of bearing) and a time interval. A report can also contain other properties of the observed object such as identifiers or classification information. The correlation process combines reports of the same type to form tracks. Under the three-tier information architecture, tracks are really clusters of reports from a given sensor system that are all observations of the same entity. Multi-source correlation associates tracks from different sensors or reporting systems with each other and with the specific entities that they represent. Entities can be any militarily significant objects that the commander must deal with, such as platforms, masses of troops, targeted sites, or friendly assets.

The XTCF framework will permit adding new report sources and report types to an existing system. These new report types may have a corresponding new track type or they may be reports for an existing track type. Similarly, a new track type can use an existing type of report. All track types are candidates for entity association.

Separation of Responsibilities

A plug-in architecture such as XTCF repartitions the responsibilities of the developer and system integrator. In fact, the developer becomes a component developer, and the system integrator now takes on many of the developer's concerns regarding intercomponent communication. The developer is responsible for what data his module produces and/or consumes; the integrator is responsible for certifying components for installation and the data flow necessary for the correct functioning of the system. The component developer now can focus on the specific task at hand, rather than with system issues. This separation of responsibilities lowers the barriers to entry for component developers and speeds the injection of new technology.

Principle Core Enterprise Services

XTCF will run across multiple host platform environments. As such, XTCF development will leverage the following core technologies to form the foundation for the XTCF environment:

- Messaging Services (Publish/Subscribe)
- Extensible Markup Language (XML)
- XML Schema
- Universal Discovery and Description Interface (UDDI)
- Simple Object Adcess Protocol (SOAP)
- Web Services Description Language (WSDL)
- Lightweight Directory Access Protocol (LDAP)

Principal C^2 Components

The following XTCF software components support the three-tier architecture concept:

- Report Manager(s)
- Track Correlator(s)
- Track Manager(s)
- Entity Correlator(s)
- Entity Manager

Distributed Concepts

The principal purpose of an XTCF-based system is to provide an SOA. This objective implies that XTCF will consist of several processes running on many machines within a network. Each process will consist of one or more loosely coupled software components that run within the XTCF runtime environment. This environment provides a minimal infrastructure for XTCF components to co-exist, while sharing information and common services without interfering with each other. A standard network timing protocol will facilitate temporal synchronization of the processes. Each event can have a tag to note time of generation.

The Messaging Service

The backbone of XTCF will consist of a message publication facility that allows one component running in one process to send messages to another component running in another process. The XTCF Messaging Service (XMS) is one of the principal software components of the framework. XMS will provide asynchronous, reliable message exchange between XTCF components. In the Java environment, XMS will build on the JMS messaging specification for inter-process messaging.

OPERATIONAL CONCEPT

Naval, joint, and coalition operations increasingly use a broad variety of organic and non-organic ISR data sources including traditional "INTS" (SIGINT, MASINT, IMINT, HUMINT, etc.), Tactical Data Information Links (TADILs), and reference databases. This continually increasing volume of data stresses today's Common Operational Picture (COP) architecture to its limits. The new net-centric approach allows naval, joint, and coalition forces to operate in a networked information domain that has the capability to share and exchange information among geographically distributed forces including sensors, decision-makers, and shooters. This domain provides access to assured information whenever and wherever needed. This coherent view of the battlespace, from space to sea bed, will provide the Information Superiority required in today's dynamic environment.

Operational payoffs will include the following:

- Improving a Commander's situational analysis, awareness, and planning by leveraging the concepts of Smart Push (time-sensitive situational awareness and survival data where publishers provide streams of all available data in selected categories) and Intelligent Pull (where user queries initiate information delivery)
- Enhancing interoperability by eliminating the current Common Operational Picture maritime track-centric approach and extending wide-area network (WAN) access to operationally relevant, non-track-centric, non-geographically referenced data
- Increasing "speed-to-capability"
- Allowing tailoring of information on a plug-and-play basis to facilitate customizing and delivering the essential information and data services critical to a specified mission area
- Providing distributed access to tactical data repositories (formerly restricted to a LAN environment) to widely dispersed forces
- Making timely "raw" and processed multi-intelligence (multi-INT) data available to users
- Eliminating unique Department of Defense (DoD) data synchronization and distribution issues:
  - Data duplication at nodes—creating unnecessary processing
  - Data ringing
  - Event-based "dumb push" of sensor events—wasting needed network capacity
- Increasing the capacity of disadvantaged users to access tactically relevant data

Ultimately, these operational payoffs will realize the overall objective of a relevant, consistent, and secure representation of tactical geo-spatial data that ensures a common basis of decision-supporting information.

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Real-Time Implementation of a Matched-Field Tracker in an Autonomous Submerged Target Trip-Wire System

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ABSTRACT

Passive acoustic matched-field tracking (MFT) has been used to detect, track, and classify submerged sources operating near bottom-deployed or vertical hydrophone arrays. The feasibility of implementing an autonomous, real-time MFT tracker has been limited by many factors including algorithm complexity, limited battery capacity, and the inability to maintain accurate in situ hydrophone array element locations. Hydra project scientists and engineers developed a solution to this problem. A sensor and processing system was designed and deployed during a recent international sea test and demonstrated the practicality of using a sparse acoustic array to act as a trip-wire surveillance system. This paper describes the sensor and processing system, the at-sea deployment method, and also details real-time tracking and processing results against a towed-source target.

INTRODUCTION

Naval commanders must work against an ever-quieting submarine threat in an attempt to maintain underwater situation awareness. Contemporary, underwater passive acoustic surveillance systems help clarify this picture and, in so doing, are expected to (a) operate in complex acoustic environments; (b) be lightweight, low power, and low cost; (c) be capable of operating covertly, and (d) be mostly autonomous.

Key situational information can be provided to naval commanders by a trip-wire system (Figure 1) that indicates when a submerged, submarine-like sound source has just passed over or nearby the acoustic sensors. Networking multiple trip-wire systems form extended barriers.

Two autonomous, low-power, lightweight tripwire prototypes, Hydra and Kelp (Figure 1), have been designed and tested at sea against a submerged, towed, acoustic source. Hydra is a 650-meter, seafloor, horizontal line array (HLA), with six non-uniformly spaced hydrophones and eight non-acoustic (magnetic, tilt, and depth) sensors. Kelp is a 70-meter, vertical line array (VLA) with six uniformly spaced acoustic and four non-acoustic sensors. Compared to Kelp, Hydra's long horizontal baseline provides better x/y target estimation, while Kelp's vertical orientation provides better depth discrimination than Hydra. The matched-field tracking (MFT) algorithm [1 and 2] used in each design requires accurate array element location (AEL). Hydra uses a novel semi-autonomous time-of-arrival-based AEL estimator, while Kelp autonomously performs AEL in real time using tilt, compass, and pressure measurements taken along the array.

HYDRA AND KELP ENGINEERING

Hydra and Kelp are composed of similar components. In both systems, a string of acoustic and non-acoustic sensors are connected to a node (Figure 2). The node generates timing signals for time-division multiplex synchronization of sensor data. The received digital acoustic and non-acoustic data are processed by a 32-bit floating-point digital signal processor (DSP) and recorded to a hard-disk drive for postmortem analysis. DSP-generated target tracks are then reported via a telesonar [3] link.

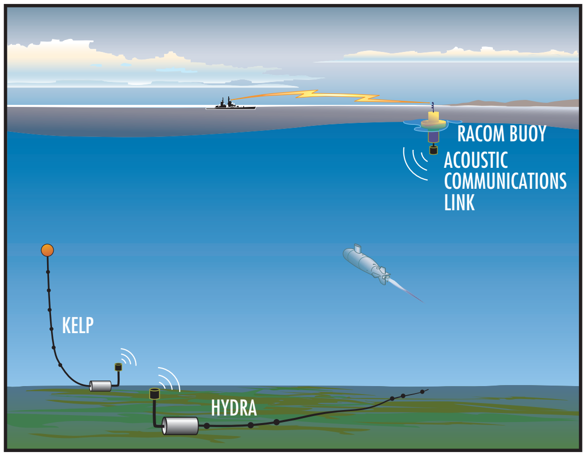

FIGURE 1. Hydra and Kelp operational concept. These two array systems autonomously run a matched-field algorithm to localize submarine sources in a trip-wire configuration.

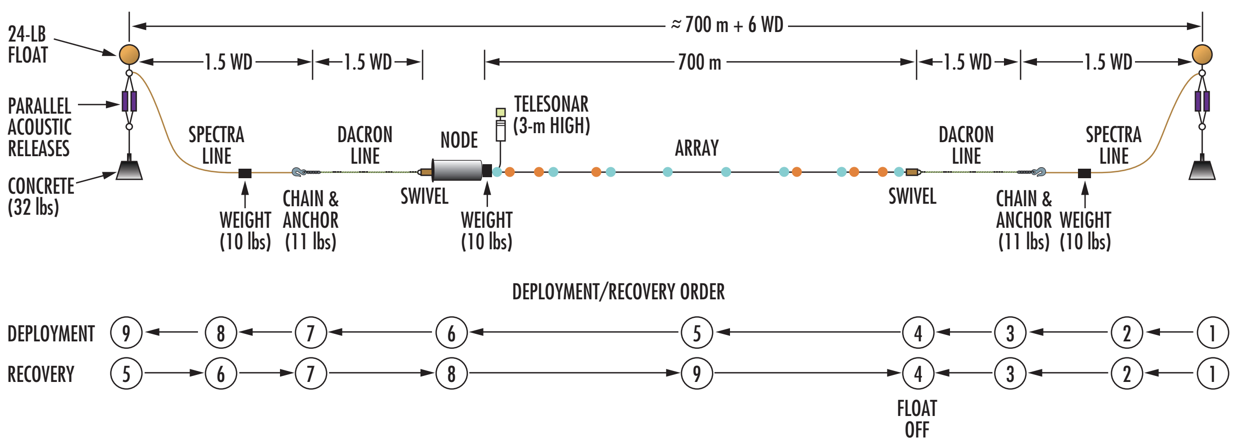

FIGURE 2. Hydra array configuration and deployment and recovery order.

CABLE DESIGN

The Hydra cable (Figure 3) uses four conductors for power and ground, with a fifth for data, and a sixth for telemetry synchronization. The specific gravity of 2.3 is sufficient to prevent current induced cable movement on most sediment types. With an overall cable diameter of 0.47 cm and weight in air of only 31.1 grams/meter, the array can be handled by two people and shipped as excess air baggage.

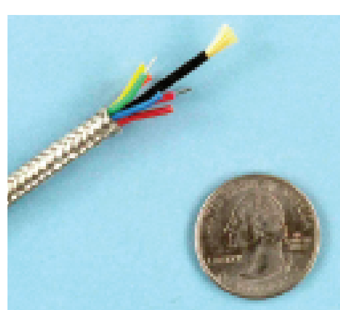

FIGURE 3. The Hydra cable consists of six 28-AWG (American Wire Gauge) conductors around a center Kevlar-strength member. The cable was designed to be very flexible and incorporates a free-flooding tinned copper braid shield overall.

ACOUSTIC SENSOR DESIGN

The Hydra acoustic sensor (Figure 4) is composed of a small, air-backed, piezoelectric hydrophone with a sensitivity of –187 dBV/uPa. A two-stage, low-noise (50 dB/uPa/root Hz over the full bandwidth), low-power, 3-volt preamplifier provides a gain of 50 dB from 10 to 200 Hz. A unity gain anti-alias filter follows the preamp. A 16-bit analog-to-digital converter samples the filter output at 600 samples per second. All digital telemetry is handled by a low-power field programmable gate array (FPGA).

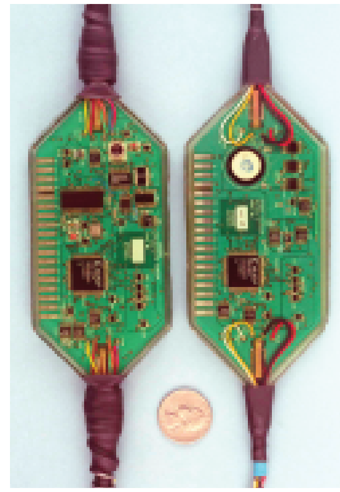

FIGURE 4. The acoustic (right) and non-acoustic (left) sensor circuit boards shown above are enclosed in a thin plastic form and filled with low viscosity polyurethane for waterproofing. Weights are added at the cable entrance and exit points to increase the package specific gravity to 1.8.

NON-ACOUSTIC SENSOR DESIGN

Non-acoustic sensors are distributed along both arrays to facilitate localization of the acoustic elements by measuring heading, tilt, and depth. In addition to the telemetry interface FPGA, each non-acoustic sensor uses a microcontroller to decode commands, control the conversion processes, and format and preprocess data. To conserve power, the microcontroller remains in sleep mode unless a command is received from the node, which controls the non-acoustic sensor sample rate (Kelp: once per minute; Hydra: once per hour). An 18-bit Sigma-Delta ADC, with integral gain and filter, samples the sensor outputs.

Array tilt (Kelp only) is measured by a two-axis accelerometer. This measurement also serves to correct the output of the three-axis heading magnetometer for tilt. The pressure sensor is exposed to ambient pressure via a small ceramic chimney filled with a pliable potting material.

TELEMETRY

Hydra and Kelp implement a noise-resistant digital time-division multiplexed telemetry scheme (Figure 5). The clock is partitioned into six acoustic data slots, one submultiplexed non-acoustic sensor slot, and a reset and command interval. Non-acoustic sensors, i.e., compass, tilt, temperature, and pressure, are multiplexed into the engineering sensor slot. The reset and command interval synchronizes the sensors and allows the node to send commands to them. A low-power FPGA in each sensor detects the reset interval, and begins an ADC; acoustic sensor outputs are simultaneously sampled. Then each sensor counts clock edges and places its data on the data conductor when its turn arrives.

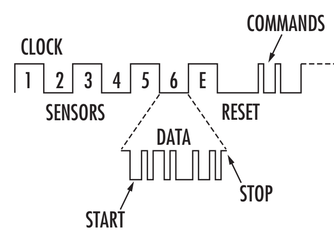

FIGURE 5. Hydra and Kelp implement a digital time-division multiplexing telemetry scheme. The FPGA in the node generates an array clock that delineates the data slot times assigned to a particular sensor.

Each data sample is an asynchronous bit stream with 2 start bits, 2 address bits to identify the data's origin, 16 data bits, and 1 stop bit. The node FPGA implements a universal asynchronous receive and transmit (UART)-style detector to decode the data stream. The data are then briefly buffered in parallel first in, first out (FIFOs) inside the FPGA and formatted for output to the DSP and data-recording subsystem.

NODE

The interchangeable Hydra and Kelp nodes (Figure 6) perform the following functions: (1) generate timing signals for multiplex synchronization, (2) send commands to the acoustic and non-acoustic sensors, (3) format the inbound digital data stream for the recording subsystem and for processing by the DSPs, and (4) report results via an underwater acoustic modem.

A significant effort was made to reduce size, weight, and average power consumption of the node. The Hydra node cylinder roughly measures 14 cm in diameter by 70 cm in length and weighs 20 kg in air and 2.7 kg in water. Each DSP board consumes approximately 3.5 watts; the balance of the circuitry, including the acoustic and non-acoustic sensors, consumes less than 1.5 watts.

Inside the canister is a collection of commercial and custom circuit cards. The node block diagram (Figure 7) shows two parallel data paths. One path is destined for the DSPs, and the other path for the raw-data recording subsystem. The block diagram also depicts the master controller card that features an 8-bit Microchip, Inc., microcontroller (PIC17C756A) that functions as a very reliable and flexible coordinator of most processes within the node.

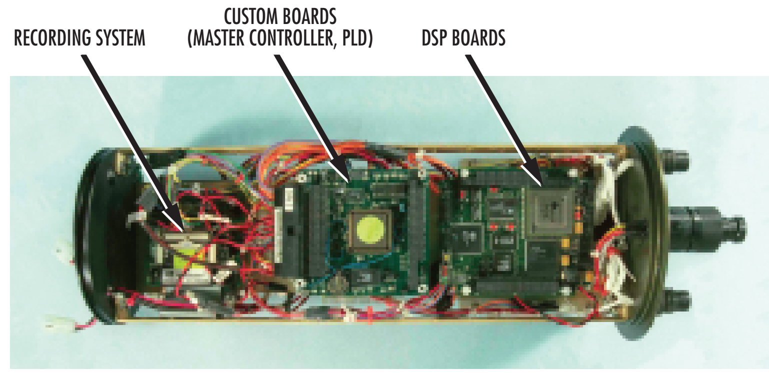

FIGURE 6. Hydra/Kelp node. The node design has evolved over 3 years and now forms a simple, yet powerful, flexible, modular, and expandable platform for evaluating advanced algorithms. Furthermore, reliable forward and backlinks, implemented through an underwater modem, provide scientists and engineers with solid control over mission execution.

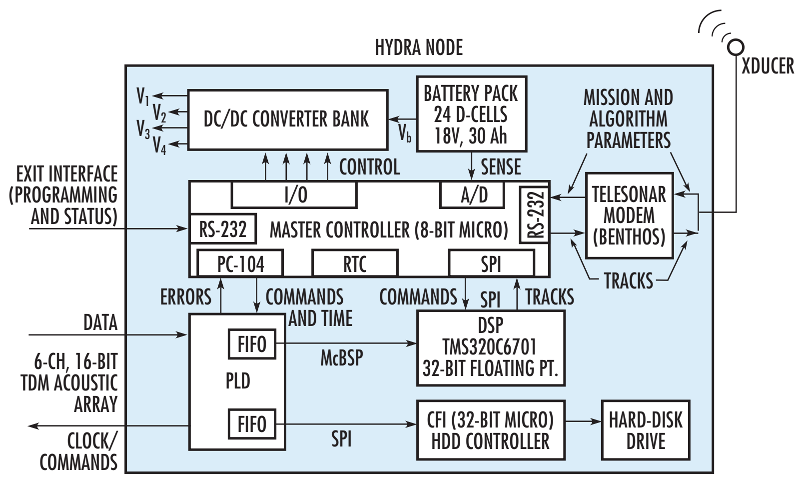

FIGURE 7. Hydra node block diagram.

DEPLOYMENT, RECOVERY, AND SYSTEM CONFIGURATION

Significant efforts have been made throughout the design process of all Hydra and Kelp subsystems to keep sizes and weights small compared to conventional acoustic-array systems. Thus, Kelp and Hydra can be deployed and recovered by only two people and one small rubber hull inflatable boat (RHIB) craft (Figure 2).

MATCH-FIELD TRACKING ON A DSP

Matched-field tracking solves for the position, course, speed, and depth of an underwater sound source by correlating acoustic spectra observed at known hydrophone locations with modeled spectra from hypothetical sound sources at various points within a five-dimensional search grid over a short processing epoch. Historically, this has been computationally and operationally demanding. Normal-mode acoustic modeling is typically time-consuming, memory-expensive, and must be tailored to each particular operating environment. The large number of Fourier frequency bins and target vector/depth grid points places a large computational burden on a processor.

Several design choices made it possible for an MFT algorithm to run in real time in an autonomous tripwire system. First, the number of Fourier bins considered was reduced to the eight strongest 0.07-Hz-wide frequency bins from an assumed narrowband threat. Second, a two-path Lloyd's Mirror-based spectral model served as a simple, yet robust, replacement for the normal-mode approach. Third, processing epochs were 3 minutes long. Fourth, the MFT evaluated each incoming track in a search grid 1000 meters wide and 2000 meters long, offset 500 meters from the receive array. Finally, the algorithm was ported to Texas Instruments' TMS320C6701 32-bit floating-point DSP, which served as a capable low-power processing device.

A submerged target track was declared if its correlation exceeded a 70% threshold. Figure 8 illustrates MFT results for two submerged source crossings of a Hydra system in 164 meters of water off Halifax, Nova Scotia.

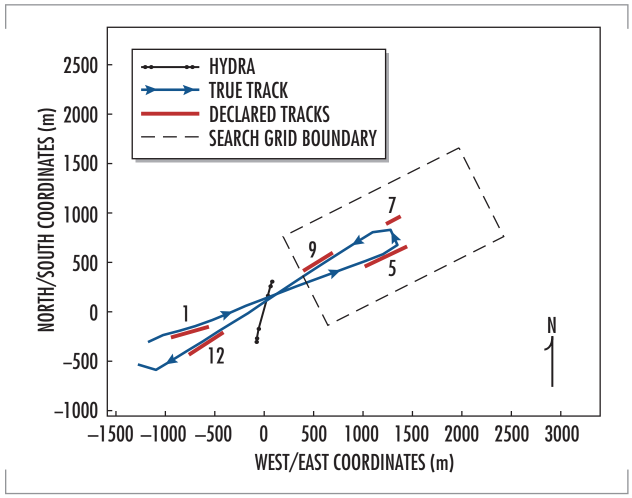

FIGURE 8. Real-time MFT over Hydra. The 4-knot, 46-meter deep source crossed Hydra twice during 12 epochs. Submerged tracks were declared for epochs 7 and 9 using the search grid shown for incoming targets. Tracks for epochs 1, 5, and 12 are derived by reorienting the grid, in situ, with Telesonar.

ADVANCED PROCESSING

For engaging threats with negligible narrowband energy, an alternative model-based process has been developed for targets with broadband signatures. This advanced process performs waveform cross-correlations for all hydrophone pairs. The key is to exploit the distinct correlation peaks associated with a multipath arrival structure as a function of range and depth. This is a distinctive fingerprint of the source location. Figure 9 shows the measured range-dependent multipath arrival structure from a towed source twice crossing Hydra off the coast of San Diego. Figure 10 shows a modeled version of this same array crossing, and Figure 11 shows the result of stacking slices versus depth at each time epoch during the array crossings.

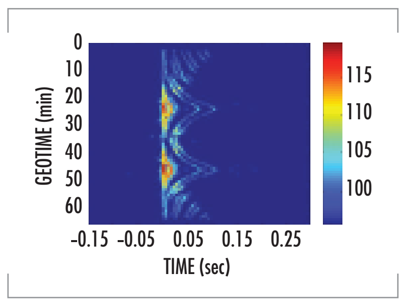

FIGURE 9. Measured multipath at a single Hydra array element during two array crossings. Note that the multipath is a distinctive fingerprint of source location.

SUMMARY

Hydra and Kelp were the first underwater passive acoustic autonomous array systems to implement an MFT algorithm in real time. The ultra-lightweight, low-power, array sensor system was the result of 20 years of research and development in underwater acoustic surveillance systems at SSC San Diego. The digital array and processing capabilities in the node represent a state-of-the-art, flexible, and modular platform for evaluating advanced processing algorithms.

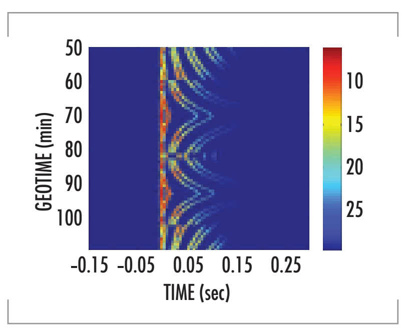

FIGURE 10. Modeled multipath at a single Hydra array element during two array crossings. The model accurately reconstructs the measured multipath shown in Figure 9.

ACKNOWLEDGMENTS

Both the Hydra and Kelp projects were funded by the Office of Naval Research (ONR) 321SS (Dr. James McEachern team leader). Project engineers Chris Fletcher and Alan Fronk and technicians Norma Blas, Carolyn Kloss, and Al Brill also made valuable contributions to the project. Special thanks goes to Mark Stevenson, who was the project manager for Hydra and Kelp for many years.

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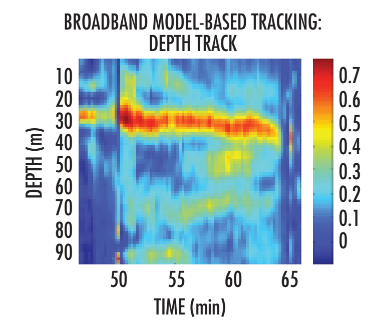

FIGURE 11. Advanced processing of broadband signature reproduced known source depth of 30 meters. Source was similarly tracked in x and y. These tracks were based on matching measured and modeled cross-correlation waveforms.

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SSC San Diego Support for the U.S. Coast Guard

David Morin
SSC San Diego

ABSTRACT

In April 2002, the Chief of Naval Operations (CNO) and the Commandant of the United States Coast Guard (USCG) signed a Joint Policy Statement that committed both services to "… work together to plan and build a National Fleet…to optimize our effectiveness across all naval and maritime missions." The statement commits the Navy and Coast Guard to "… coordinate, to the extent permitted under existing statutory authority, research and development, acquisitions, information systems …" This policy statement is an affirmation of support that SSC San Diego has been providing the USCG for many years. This paper describes work that has been done at SSC San Diego to support the two largest acquisition programs in the history of the USCG.

INTRODUCTION

The United States Navy (USN) and the United States Coast Guard (USCG) have always worked together to protect the U.S. from threats to its security and sovereignty (Figure 1). USCG vessels have deployed, and continue to deploy, with Fleet Battle Groups as required to meet the USN mission requirement. USN assets assist the USCG in its counter-narcotics and other maritime law enforcement, maritime safety, and environmental protection operations. However, regulations governing the rules of engagement for USCG and USN forces have provided a clear separation between the missions of the two services: the USCG is focused on law enforcement; the USN on military missions.

The terrorist attacks on September 11, 2001, and subsequent legislation passed by Congress, particularly the Patriot Act and the Maritime Security Act of 2002, have blurred the demarcation between law enforcement and military operations. Figure 2 shows there is now a significant portion of the enforcement continuum where the missions of the USCG and the USN overlap. The USCG's mission of homeland security now includes enforcement actions that are traditionally military in nature. The USN's mission of homeland defense now requires previously forbidden support for law-enforcement actions.

THE NATIONAL FLEET

In a Joint Policy Statement entitled "National Fleet," dated April 2002, ADM Vernon Clark, the Chief of Naval Operations (CNO), and ADM James Loy, the Commandant of the Coast Guard, stated: "…the challenges (to our sovereignty and maritime security) grow more diverse and complex each year. Regional conflict, crisis response, sanctions enforcement, arms trafficking, weapons proliferation, illegal mass migration, smuggling, natural resource depletion, force protection, weapons of mass

FIGURE 1. Homeland and maritime security in the 21st century.

destruction, and terrorism are just some of the growing challenges we face in maritime security.… Success in countering these threats will require the skillful integration of the core competencies of the Services (Navy and Coast Guard) into a joint force tailored to the specific situations and objectives.…" The policy statement commits the USN and USCG to "…work together to plan and build a National Fleet of multi-mission assets, personnel resources, and shore Command and Control nodes to optimize our effectiveness across all naval and maritime missions. The Navy and Coast Guard will coordinate, to the extent permitted under existing statutory authority, research and development, acquisitions, information systems integration, resourcing, force planning, as well as integrated concepts of operations, intelligence, logistics, training, exercises, and deployments."

This policy statement is an affirmation of the acquisition and technical support that SSC San Diego has provided the Coast Guard for many years.

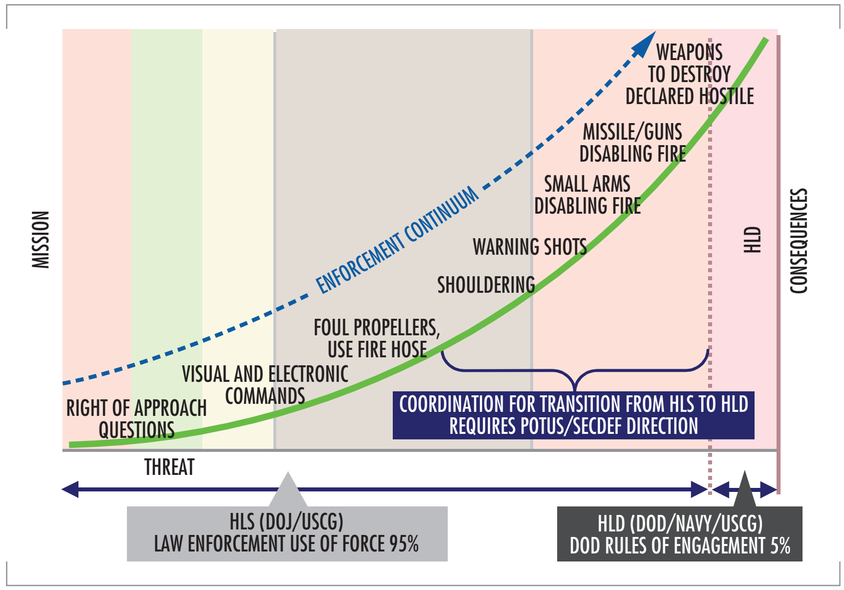


FIGURE 2. Homeland security (HLS) —Homeland defense (HLD) continuum. Acronyms: POTUS – President of the United States; SECDEF – Secretary of Defense; DOJ – Department of Justice

SSC SAN DIEGO SUPPORT FOR THE COAST GUARD

SSC San Diego has a long history of support for the USCG. Over the past two decades, SSC San Diego work has included sensor studies, command, control, communications, computers, intelligence, surveillance, and reconnaissance (C^4ISR) architecture definition, and top-side radio frequency (RF) design analyses. Since 1996, the SSC San Diego U.S. Coast Guard Support Team has made significant technical and management contributions to the two largest acquisition projects in USCG history: the Rescue 21 Project and the Integrated Deepwater (IDW) System Project. The USCG Office of Acquisition for Rescue 21 (G-AND) and the Office of Operational Capabilities (G-OC) sponsor the Rescue 21 support work. The USCG Office of Acquisition for IDW (G-ADW) is the sponsor for IDW tasks. General Dynamics Decision Systems, Scottsdale, AZ, is the prime contractor for Rescue 21. Lockheed-Martin is the prime for the IDW Systems project.

RESCUE 21 SYSTEM DEVELOPMENT SUPPORT

The Rescue 21 system is a short-range, very-high-frequency (VHF) communications system that supports the operational missions of USCG groups, small boat stations, air stations, marine safety offices, and Captains of the Port along all coastlines, major lakes, and inland waterways in the continental U.S., Alaska, Hawaii, Guam, and Puerto Rico (Figure 3). Rescue 21's primary functions are to monitor for maritime distress calls and to provide command and control capabilities for USCG assets operating in regions near the coast. The Rescue 21 system is a multi-year, $1.5 billion project to modernize and expand the capabilities of the current, 1970s-era system. Table 1 compares capabilities of the Rescue 21 system to those of the existing system.

The SSC San Diego USCG Support Team has supported the Rescue 21 program since its inception. Team members have performed multiple analyses, developed technical and project documentation, and performed technology demonstrations

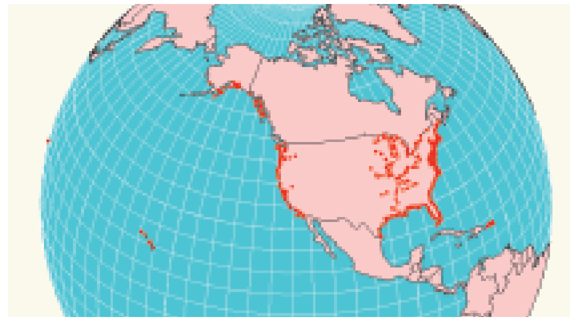


FIGURE 3. Rescue 21 site locations.

TABLE 1. Rescue 21 improvements.

Capabilities		Existing System	Rescue 21
Monitor Distress Calls	Continuous Uninterrupted Channel 16 VHF-FM Guard	NO	YES
	Channel 70 VHF-FM DSC	NO	YES
	Communications Coverage	> 80 Gaps	98% Area Coverage
	Direction Finding	NO	YES
Alert Response Assets	Automatic Asset Tracking	NO	YES
	Data Communications	NO	YES
Coordinate Response Activities	Public Safety Interoperability	NO	YES
	Full Coverage for Protected Communications	NO	YES
	Automatic Marine Broadcasts	NO	YES
	Geographic Display	NO	YES
	Number of Simultaneous Communication Channels	1	6
	Archiving/Recording	Voice	Voice/Data
	Operational Availability	Unknown	99.50%
	Recoverability	No Systematic Plan	24 hrs for Critical Functions

required to achieve key acquisition program decision points. Successful accomplishments include development of acquisition approach analyses, cost-performance trade-off analyses, life-cycle cost analysis, test plans and procedures, sensor and communications technology assessments, communications coverage analyses, the system performance specification, and the statement of work for system acquisition. The SSC San Diego team supported source selection, including development of evaluation criteria and standards, and team members participated as source selection board members. Subsequently, they monitored and evaluated the contractor's work and technical documentation during the program's exploratory development phase. The SSC San Diego USCG Support Team is also the Operational Test and Evaluation agent for the Rescue 21 system when it is initially delivered in the first quarter of fiscal year (FY) 04 and is responsible for inspection and certification of production installations in the Pacific region in FY 04 to FY 06. A significant achievement of the USCG Support Team was a successful Advanced Concept Technology Demonstration (ACTD) of Radio Direction Finding (RDF) and Digital Selective Calling (DSC) for the USCG and the later transition of the system to operational use by USCG Activities San Diego. Figure 4 shows the architecture of the RDF/DSC ACTD.

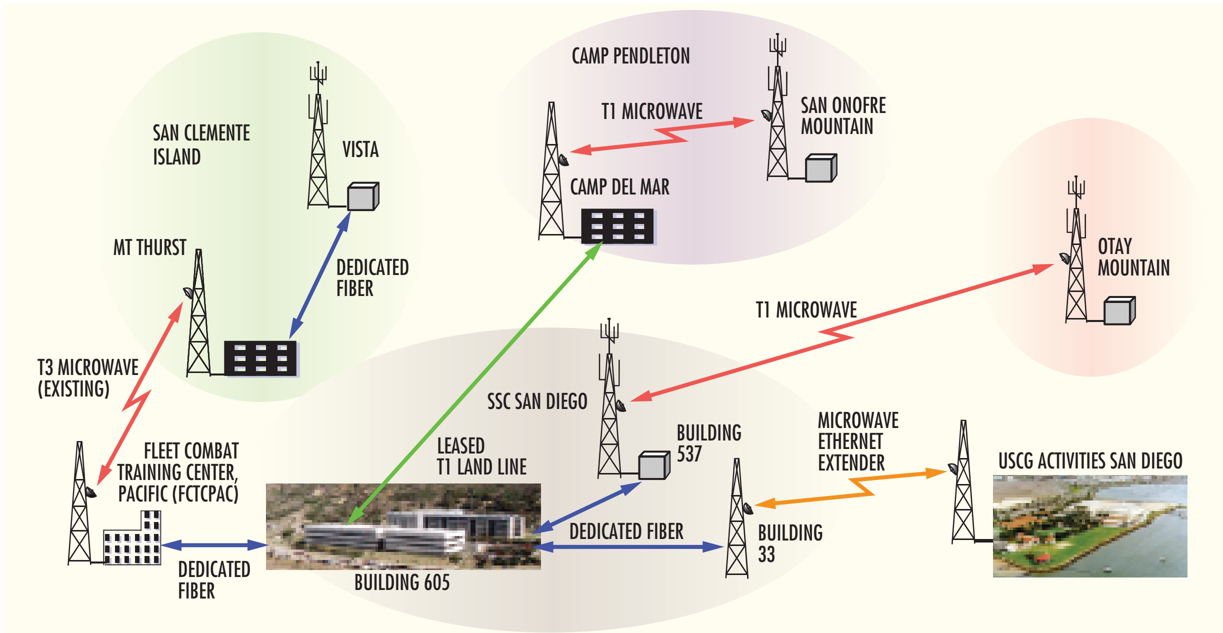


FIGURE 4. Radio Direction–Digital Selective Calling ACTD.

INTEGRATED DEEPWATER SYSTEMS PROJECT SUPPORT

The Integrated Deepwater (IDW) Systems project is a multi-billion dollar, multi-year project to re-capitalize an aging fleet of 206 aircraft and 93 cutters and replace the current collection of obsolete systems with an integrated C4ISR solution. Figure 5 describes this transformation. SSC San Diego support for the USCG IDW Systems program includes providing critical management personnel and a variety of systems engineering and technical expertise. An SSC San Diego employee is serving as C4ISR Technical Director for the IDW Systems project. Additionally, in a true example of the cooperative effect called for in the National Fleet Policy Statement, SSC San Diego-based subject matter experts have served as members of a "Virtual Laboratory Team" established by the USCG to augment its own technical personnel in support of IDW Systems development. SSC San Diego team members have been drawn from all Departments. Major contributions have included review of contractual and technical aspects of the IDW Systems Request for Proposal, and review of C4ISR and architecture products developed by the Prime Contractor.

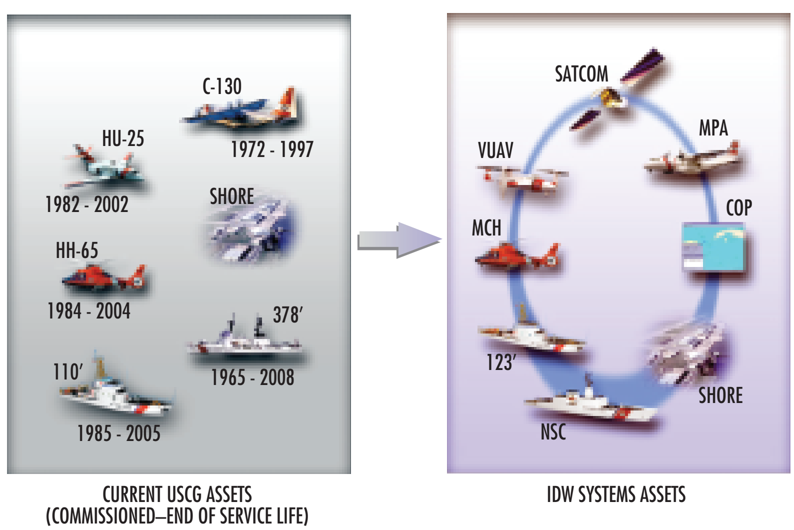


FIGURE 5. IDW systems re-capitalization of USCG assets.
Acronyms: MPA – Maritime Patrol Aircraft; COP – Common Operating Picture;
NSC – National Seurity Cutter; MCH – Mission Cutter Helicopter;
VUAV – Vertical-Launch Unmanned Air Vehicle

Team members also served as technical consultants during evaluation of Offerors' proposals.

The SSC San Diego USCG Support Team has also provided technical data about DoD C^4ISR Systems of Record and about Navy research and advanced development efforts applicable to the IDW Systems Program, surveyed programs of record for Level of Information System Interoperability, and defined key test and evaluation processes. SSC San Diego involvement in the IDW Systems program is expected to continue as the project evolves from acquisition to systems engineering to development to test and evaluation through FY 08.

TEAM REWARDS AND CHALLENGES

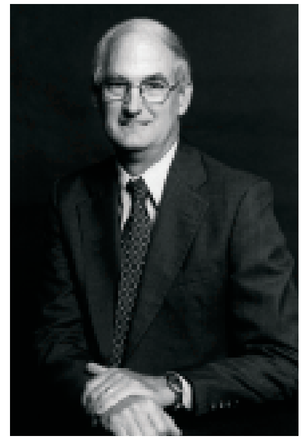
There have been many rewards and a few challenges in working with the USCG. SSC San Diego USCG Support Team members have received great personal rewards from being able to apply their acquisition and technical expertise from the project's inception and have seen their inputs improve USCG C^4ISR capabilities. Other, more tangible rewards are a USCG Meritorious Team Commendation for Rescue 21 TDA support received in April 1999 and an SSC San Diego Center Team Achievement Award received in 2002. To accomplish these achievements, the team has had to meet several challenges, not the least of which is an extremely aggressive schedule, imposed by Congress, that has required significant adaptation of the traditional DoD acquisition—system engineering—system development processes. Table 2 depicts other challenges and the methodologies used by the team to overcome the challenges. We expect additional challenges as the Coast Guard transitions into the Department of Homeland Security.

TABLE 2. Mitigation methodologies for project challenges.

Challenge	Mitigation Approach
Performance-based contracting for very complex systems	• Careful review of requirements • Use of DOORS® for requirements traceability • Use of modeling and simulation to validate system performance • Integrated Product Teams
Developing a "Joint Team" environment while working with geographically dispersed personnel	• Lotus Sametime™ and Lotus Domino™ based collaborative processes • Project Web site • Frequent team status and information meetings • Integrated Product Teams
Obtaining SSC San Diego subject matter experts on demand for quick-response, short-duration tasks when the most highly qualified personnel are already fully tasked	• Use of Microsoft Project™ for planning • Pre-arranged support agreements with key personnel • Good inter-division and inter-department working relationships at SSC San Diego
Working with a non-DoD Sponsor	• Special processes for funds processing by SSC San Diego Accounting and Defense Finance and Accounting Service (DFAS) • Dedicated Financial Analyst • Project Web site for information management

CONCLUSIONS

SSC San Diego personnel have provided significant acquisition planning and engineering support to the two largest acquisition efforts in USCG history. Team contributions have been critical in successfully achieving major project milestones and will enable the establishment of a greatly improved C^4ISR capability for the USCG. This work is a successful example of the cooperative efforts cited in the "National Fleet" Joint Policy Statement signed by the CNO and the Commandant of the USCG.



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An Artificial-Neural-Network Multiple-Model Tracker

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ABSTRACT

A neural extended Kalman-filter (NEKF) algorithm was embedded in an interacting multiple-model architecture for target tracking. The NEKF algorithm is used to improve motion-model prediction during maneuvers. With a better target motion mode, noise reduction can be achieved through a maneuver. Unlike the interacting multiple-model architecture that uses a high-process noise model to hold a target through a maneuver with poor velocity and acceleration estimates, an NEKF is used to predict the correct velocity and acceleration states of a target through a maneuver. The NEKF estimates the weights of a neural network, which, in turn, is used to modify the state estimate predictions of the filter as measurements are processed. The neural-network training is performed online as data are processed. This paper provides the results of an NEKF embedded in an interacting multiple-model tracking architecture. Highly maneuvering threats are a major concern for the Navy and Department of Defense (DoD), and this technology will help address this issue.

INTRODUCTION

The Robust Tracking with a Neural Extended Kalman Filter (NEKF) project is an Office of Naval Research (ONR) In-house Laboratory Independent Research (ILIR)-sponsored effort at SSC San Diego. The project's goal is to provide an improved state estimation capability for current U.S. Navy tracking systems. The NEKF will provide added capability for the real-time modeling of maneuvers and, therefore, will enhance the ability of tracking systems to adapt appropriately.

Extended Kalman filters using neural networks have been utilized in the past in control-system technology and for system identification [1 and 2]. This paper details how the NEKF can be incorporated into an interacting multiple-model tracking architecture to provide robust tracking capabilities that are currently unavailable.

BACKGROUND

State estimation and tracking of highly maneuvering targets are extremely difficult tasks in modern tracking systems. Current state estimation approaches to the tracking problem include alpha–beta filters, Kalman filters, interacting multiple-model (IMM) filters, probabilistic data association (PDA) trackers, and joint PDA (JPDA) trackers [3 and 4]. State estimation is the problem of deriving a set of system states that are of interest to a system or decision-maker. System states consist of parameters such as position, velocity, frequencies, magnetic moments, and other attributes of interest. Most often, system states are not measurable at the system output. For example, range and bearing of a target may be available from a radar sensor, but the position and velocity of the target need to be derived from the radar measurement. To derive these states, an estimation algorithm is used. A mathematical system model is necessary for the aforementioned filter algorithms to perform state estimation.

Kalman Filter

A well-known state estimation algorithm is the Kalman filter developed four decades ago by R. E. Kalman [5]. The Kalman filter is widely used in government and industry tracking problems. The Kalman filter uses an assumed mathematical system model (i.e., a straight-line motion model for an aircraft) to estimate the states (position, velocity, signatures, etc.) of an aircraft. A Kalman filter consists of the dynamic system to be tracked, a mathematical system model, an observation model, the Kalman gain, a predicted observation, and the system state vector. The Kalman filter is a recursive estimation algorithm that is driven by the observation data from the dynamic system. As data are processed, a filtered estimate of the state is generated by the filter. As long as the dynamic system is linear and matches the assumed motion model, the filter will perform quite well, and tracking will be successful. A problem occurs when the aircraft or system being tracked changes from the assumed motion model. The filter will tend to lag behind the true state of the target or even diverge and become unstable and unable to estimate the system states. In cases where the motion model and/or the observation model are nonlinear, an extension of the linear Kalman filter must be used. A nonlinear extension of the Kalman filter is the extended Kalman filter (EKF) [6]. The EKF is used to handle known nonlinearities. When it comes to tracking moving targets, it is not known what the craft will necessarily do next. This uncertainty causes a problem with trying to model or account for a good motion model for the filter to use.

Interacting Multiple-Model Filter

Another well-known state-of-the-art tracking technique is the IMM filter [7]. This technique employs multiple models (a bank of Kalman filters) to perform state estimation. Each model may contain a different mathematical system model, observation model, variable dimensional state, or noise processes. For example, an IMM filter could consist of two Kalman filters, both using a straight-line motion model and differing by a low-process noise model and a high-process noise model, respectively. The two models are mixed probabilistically to fit the dynamics of a target. As long as a target follows a straight-line motion and does not deviate from it, the first model will be in effect. As a target maneuvers from a straight-line motion, the second model goes into effect, and in a sense, the noisy radar measurements are connected together yielding a very poor velocity estimate of the target during the maneuver. The IMM architecture can also be used with an EKF as one of its models.

Extended Kalman-Filter Neural-Network Training

If a nonlinear model is unattainable, then a system identification technique could be used to create a model. In the late 1980s to early 1990s, artificial neural networks were a popular technology. A neural network is a function approximation technique. Given a set of inputs and a desired set of outputs, a neural network could be trained to approximate any function. A neural network can be thought of as a nonlinear polynomial in which the coefficients of that polynomial must be found to approximate a desired function. Neural networks contain a set of weights (coefficients) that must be determined in order to approximate functions. To train neural networks, techniques such as backpropagation [8] and the extended Kalman filter [9] have been used. In [9], Singhal and Wu asked the question, "Why not use a Kalman filter to estimate the weights (states) of a neural network?" What they hypothesized was that the weights of a neural network are also the states of the network. The EKF training technique trains networks on the order of tens of iterations instead of thousands of iterations for such methods as backpropagation. Eq. (1) shows a neural-network equation.

$$NN_m = \sum_{i=1}^{N} w_{im} * \left(f_i \left(\sum_{k=1}^{J} I_k * w_{ki} \right) \right), \qquad (1)$$

where $f_i = \frac{1}{1 + \exp(-x_i)}$ is the output of the i^{th} hidden node, x_i is the dot product sum of the previous input layer's output with the connecting weights of the hidden layer, NN_m is the m^{th} output of the neural network, w_{im} is the m^{th} output weight connected to the i^{th} hidden node, w_{ki} is the k^{th} input weight connected to the i^{th} hidden node, and I_k is the k^{th} input feeding the neural network.

Neural Extended Kalman Filter

The NEKF developed by Stubberud [1] is based on the Singhal and Wu EKF neural-network trainer. The algorithm uses a Kalman filter to estimate the states by using a linear system model and, at the same time, using the Kalman filter to train a neural network to calculate the nonlinearities, mismodeled dynamics, higher order modes, and other facets of a system. Estimation of the system states is performed at once without the necessity of modeling the nonlinearities a priori as in the case of the extended Kalman filter. The inputs to the neural network are the updated states of the filter. The inputs are passed through an input layer, a hidden layer with nonlinear squashing functions, and an output layer. The outputs of the neural network are nonlinear corrections to the linear predicted state of the underlying Kalman filter.

NEKF IMM ALGORITHM

The NEKF IMM algorithm was developed under this ILIR project. The IMM architecture allows for Kalman-filter models of different state dimensions to be mixed together appropriately. In order to mix the NEKF's state vector and covariance matrix with the other two linear Kalman-filter models, care had to be taken. To keep a positive definite covariance matrix of the neural-network model, the mixing probability of the interacting multiple-model architecture had to be applied to the artificial-neural-network weights and covariance matrix. At first glance, it was not obvious to weight probabilistically the weight vector and weight covariance matrix of the NEKF by the mode probability. Once the probability weighting was incorporated and had stabilized the neural-network covariance matrix, a different sigmoid squashing function had to be implemented. By weighting the neural network with its mixing probability, the weight vector tended toward zero, which caused the weights to be untrainable. What caused the weights to be untrainable was using a hyperbolic tangent function as a sigmoid-squashing function that varied from [–1, 1]. A new sigmoid varying from [0, 1] allowed for a derivative of 0.5 if the weights of the neural network were equal to 0.0. This allowed the weights to be trainable if they were initialized to zero or tended toward zero. Once this was incorporated, the neural network was able to be trained inside an IMM architecture.

RESULTS

The scenario consisted of a single target moving in a circular motion for 500 seconds. The speed of the target was 50 meters per second, and the angular rate of the turn was –10 degrees per second. The sampling rate of the radar was one sample per second. There were 500 samples for each Monte Carlo run. Figures 1 through 5 and Table 1 are the 100 Monte

Carlo run results for a single EKF, a three-model IMM, and a three-model NEKF IMM. Figure 1 is the position error of each of the three filters (EKF, IMM, and NEKF IMM). The NEKF IMM has the lowest position error overall. The NEKF IMM position error is 8 meters lower on average than the EKF and 3 meters lower on average than the IMM. Figure 2 is the velocity error of each of the three filters (EKF, IMM, and NEKF IMM). The NEKF IMM has the lowest velocity error overall. The NEKF IMM velocity error is 4 meters per second lower on average than the EKF and 2 meters per second lower on average than the IMM. Figure 3, the speed error, is quite different from the first two figures. The extended Kalman filter has the best speed error, and the NEKF IMM has the worst speed error. The EKF speed error is 7 meters per second better

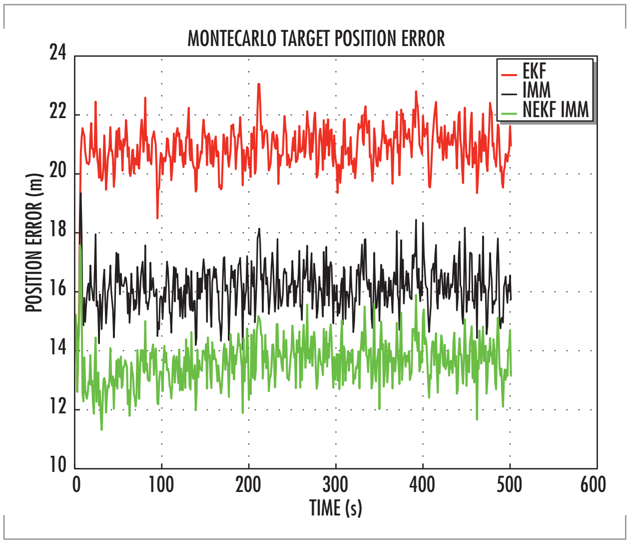

FIGURE 1. NEKF IMM, IMM, and EKF position errors for 100 Monte Carlo runs.

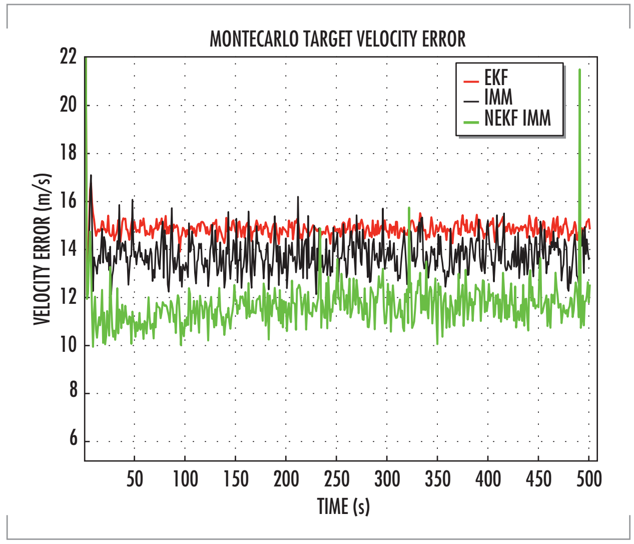

FIGURE 2. NEKF IMM, IMM, and EKF velocity errors for 100 Monte Carlo runs.

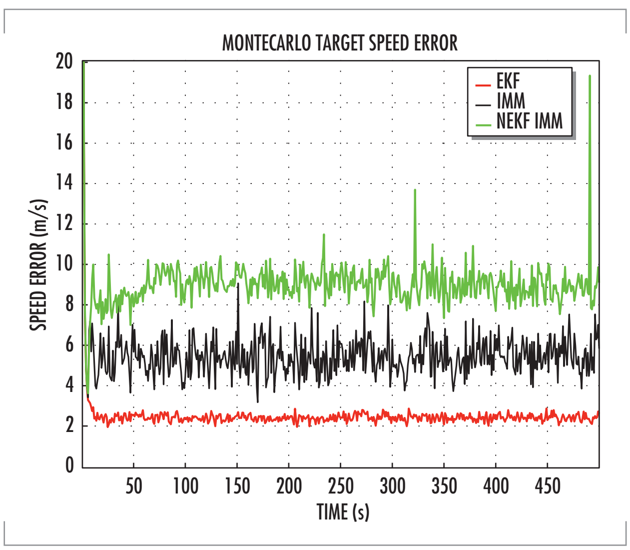

FIGURE 3. NEKF IMM, IMM, and EKF speed errors for 100 Monte Carlo runs.

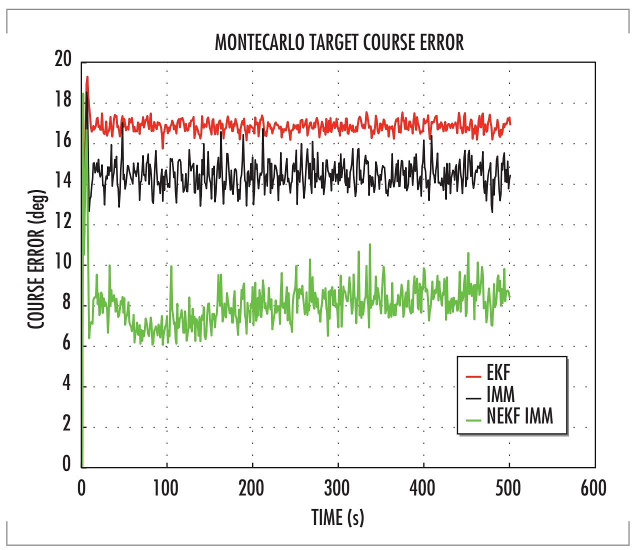

FIGURE 4. NEKF IMM, IMM, and EKF course errors for 100 Monte Carlo runs.

on average than the NEKF IMM and 3 meters per second better on average than the IMM. Figure 4 is the course error, and it shows, once again, the NEKF IMM having a much smaller error than the other filters. The NEKF IMM course error is 9 degrees lower on average than the EKF and 6 degrees lower on average than the IMM. Table 1 shows the peak errors from all four statistics (position, velocity, speed, and course). The NEKF IMM has the smallest peak error for position, velocity, and course. What this implies is that the velocity vectors for the NEKF IMM were more accurate than the EKF and the IMM filters. Since the velocity vectors were pointing closer to truth, the position error for the NEKF IMM was much smaller than the EKF and IMM filters. For the peak speed error, the NEKF IMM performed the poorest. The reason for this was that the neural network inside the NEKF IMM was over-correcting the velocity estimates at each prediction. This over-correction was due to the lag in adaptation. Nevertheless, the NEKF IMM outperformed the EKF and IMM in all but one of the error statistics. Figure 5 is a plot that shows the error reduction in position as time progresses. The plot is an ensemble average of a Monte Carlo average. Both the IMM and the EKF provide little or no error reduction in the figure. In fact, they do worse than just following the noisy measurements. The NEKF IMM continually increases positively showing that it is consistently performing better than the noisy measurements alone and performing noise reduction throughout the maneuver.

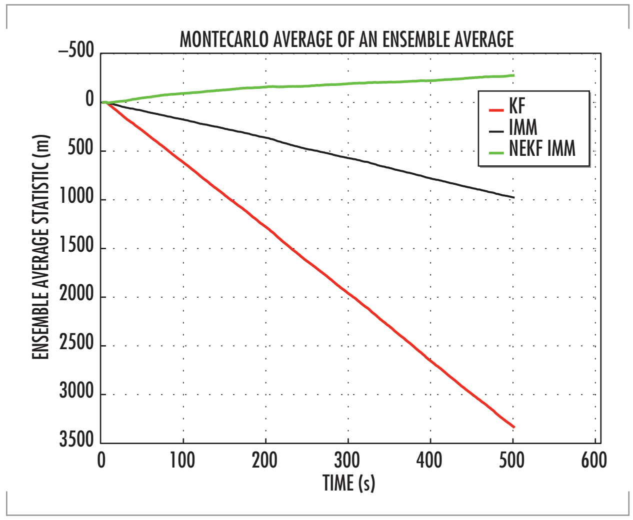

FIGURE 5. NEKF IMM, IMM, and EKF ensemble average for 100 Monte Carlo runs.

TABLE 1. Peak errors for 100 Monte Carlo runs.

Peak Errors	NEKF IMM	IMM	EKF
Position (m)	15.9	18.4	23.0
Velocity (m/s)	21.5	16.2	15.5
Speed (m/s)	19.3	9.1	2.9
Course (deg)	11.1	17.0	17.6

CONCLUSIONS

This paper described the NEKF embedded in an IMM architecture for the target-tracking problem. The NEKF uses a neural network to adapt online to unmodeled dynamics or nonlinearities in the target trajectory. This online adaptation provides for a robust state estimation for tracking applications because the maneuvers do not have to be known beforehand. The NEKF is a generic state estimator that can be used to estimate any state vector such as position, velocity, magnetic moment, frequency signatures, etc. Comparisons were performed with an extended Kalman filter, a three-model IMM filter, and an NEKF IMM with three models. The NEKF IMM outperformed the other filters in every case except for speed error. Further investigation into why the NEKF IMM did not outperform the filters in speed is now under investigation.

This technology may be the subject of one or more invention disclosures assignable to the U.S. Government, including N.C. #84224. Licensing inquires may be directed to: Office of Patent Counsel, (Code 20012), SSC San Diego, 53510 Silvergate Avenue, Room 103, San Diego, CA 92151–5765; (619) 553–3824.

ACKNOWLEDGMENTS

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Enabling Undersea ForceNet with Seaweb Acoustic Networks

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ABSTRACT

Seaweb networks with telesonar signaling are the basis for future undersea sensor grids. Node-to-node ranging is a by-product of telesonar communications, permitting sensor localization and navigation of mobile nodes such as submarines and autonomous vehicles. Seaweb networking facilitates data fusion and other collaborative behaviors and can incorporate clusters of high-bandwidth, acoustic local-area networks. Various communication gateways serve to interface the distributed Seaweb nodes with command centers ashore, afloat, submerged, aloft, and afar.

INTRODUCTION

U.S. Navy undersea wireless network development is following a concept of operations called Seaweb [1]. Through-water acoustic signaling (telesonar) using digital communications theory and digital signal processor (DSP) electronics is the basis for these underwater networks [2 and 3]. As depicted in Figure 1, Seaweb is tailored for battery-limited, expendable network nodes comprising wide-area (order 100 to 10,000 km^2) littoral antisubmarine warfare (ASW) sensor grids such as the Deployable Autonomous Distributed System (DADS) [4], and Seaweb is also tailored for off-board sensor systems such as Kelp and Hydra [5]. Seaweb has also been applied to long-term synoptic observation by distributed oceanographic sensors [6] in situations where cabled or buoyed sensor arrays would have been vulnerable to trawling, pilfering, and ship traffic. Seaweb networking provides acoustic ranging, localization, and navigation functionality, and thereby supports the participation of mobile nodes, including submarines [7] and collaborative autonomous undersea vehicles (AUVs) [8]. Seaweb networking can include clusters of nodes forming a high-bandwidth, wireless, acoustic local-area network (Sealan) that operates at higher frequencies than the Seaweb wide-area network. The Seaweb blueprint accommodates the incremental introduction of directional, channel-adaptive, situation-adaptive, self-configuring, self-healing mechanisms required for unattended operations in littoral waters. Seaweb networking includes a repertoire of communication gateways serving as interfaces between the distributed undersea sensor nodes and manned command centers ashore, afloat, submerged, aloft, and afar.

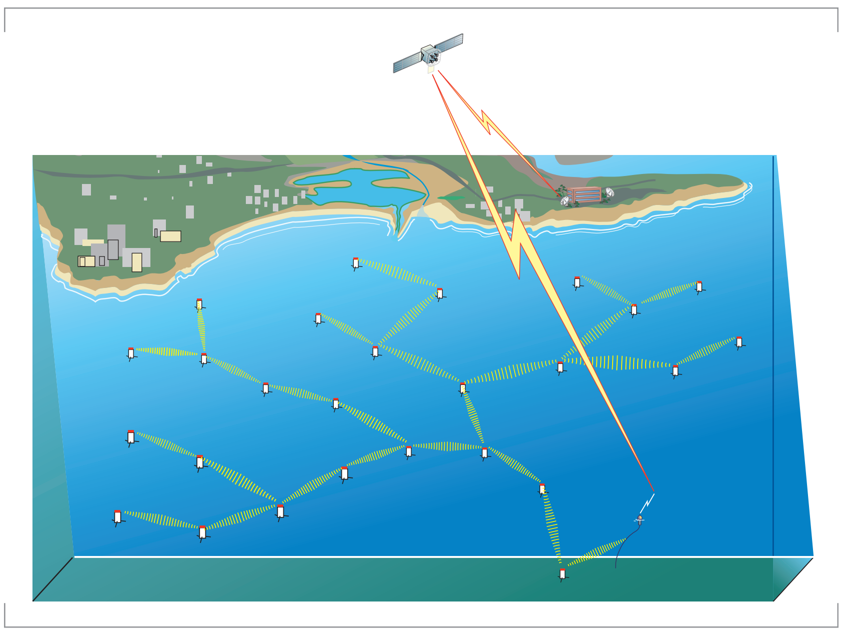

FIGURE 1. Seaweb through-water acoustic networking enables data telemetry and remote control for undersea sensor grids, vehicles, and autonomous instruments. Telesonar modems form the wireless undersea links. Gateways to manned control centers include adaptations to submarine sonar systems (Sublink) and radio/acoustic communication (Racom) buoys with links to sky or shore.

OPERATIONAL REQUIREMENT

Seaweb is the undersea component of the ForceNet seabed-to-space networked connectivity described by the Sea Power 21 vision for future naval operations [9]. The SSC San Diego Seaweb Initiative is advancing telesonar technologies and Seaweb concepts of operation for the emerging repertoire of off-board and deployable undersea systems. Telesonar acoustic links interconnect distributed underwater assets, forming Seaweb networks for coordinated autonomous operations, undersea dominance, and assured access.

Undersea operations involving autonomous systems mandate the need for digital, wireless communication and navigation. The Seaweb networks formed by telesonar links must be reliable, flexible, affordable, and secure. Telesonar transmission channels include shallow-water environments with node-to-node separations hundreds of times greater than the water depth. Seaweb must perform in the presence of severe channel impairments, battery-energy constraints, and asymmetric links, and so must be environmentally and situationally adaptive. Undersea vehicles may navigate through a fixed Seaweb grid and must maintain continuous network connectivity.

Radio/acoustic communications (Racom) buoys must permit bi-directional access to submerged sensor grids for maritime patrol aircraft and remote command centers. Similarly, submarines must communicate with off-board sensors, battle group commanders, joint task force commanders, special operations forces, unmanned aerial vehicles (UAVs), unmanned underwater vehicles (UUVs), coalition forces, and the National Command Authority. With Sublink adaptations to organic submarine sonar, the Seaweb infrastructure must accommodate in-stride connectivity at speed and depth.

Warfare considerations stipulate that the network architecture support rapid configurability, wide-area coverage, long standoff range, and invulnerability. Seaweb must support interoperability for a wide variety of cross-mission, cross-system, cross-platform, and cross-nation applications.

TECHNICAL APPROACH

Seaweb development demands attention to the underlying critical issues of adverse transmission channel, asynchronous networking, battery-energy efficiency, information throughput, and cost. The Seaweb Initiative follows a spiral development process involving applied research, incremental prototypes, and periodic testing at sea [10].

At the physical layer, an understanding of the transmission channel is gained through propagation physics theory and ocean testing. SSC San Diego has produced numerical physics-based channel models [11] and portable telesonar testbeds [12] for controlled sea measurements with high-fidelity signal transmission, reception, and data acquisition. Knowledge of the fundamental constraints on telesonar signaling translates into increasingly sophisticated digital communications techniques matched to the unique characteristics of the underwater channel. Variable amounts of forward-error correction allow for a balance between information throughput and bit-error rate.

At the link layer, compact utility packets are well suited to meeting the constraints of slow propagation, half-duplex modems, limited bandwidth, and variable quality of service. The telesonar handshaking process permits addressing, ranging, channel estimation, power control, and adaptive modulation [13]. Reliability is enhanced through the implementation of negative acknowledgements, range-dependent timers, retries, and automatic repeat requests [14].

At the network layer, routing and navigation are accomplished through embedded data structures distributed throughout the network. Critical source-to-destination connectivity can be monitored through the use of receipt utility packets. The Seaweb server maintains these data structures, supports network configurability, manages network traffic at the gateways, and provides the graphical user interface for client workstations at manned command centers [15].

Localized clusters of autonomous assets (e.g., sensors, crawlers, and divers) assimilate through the formation of a Seaweb acoustic local area network (Sealan) covering an undersea region up to 5 km^2. A central Sealan node collects high-bit-rate, digital acoustic transmissions from the Sealan peripheral nodes. The sophisticated central node receives Sealan traffic with the processing gains afforded by coherent processing, adaptive equalization, spatial diversity, and beamforming. Received data pass to a host computer for local-area data fusion. Through asymmetric low-bit-rate backlinks, the central node can adapt the peripheral nodes to an evolving search-space situation and otherwise performs networking overhead functions, including ranging, localization, navigation, and remote control. The peripheral nodes may use the low-bit-rate link format for peer-to-peer communications, including network-layer token passing and ranging. For undersea communications to beyond the local area, the Sealan central node uses Seaweb wide-area networking to cue neighboring Sealan central nodes, and to report events of interest to distant command centers by using Seaweb's decentralized wide-area networking. Sealan acoustic networks operate in a higher frequency band and with different transducers. Therefore, the central node can maintain simultaneous Sealan and Seaweb communications without suffering interference. The centralized approach for local-area networks is identified as a solution consistent with the desire for information convergence and with the constraints of undersea acoustic propagation. The central node orchestrates the overall performance of the local sensors and communications and is the local interface to the wide-area deployment. Since high-bit-rate transmitter and low-bit-rate receiver are simple, the peripheral nodes can be inexpensive, small, and plentiful.

EXPERIMENTAL IMPLEMENTATIONS

Seaweb is implemented as Navy-restricted firmware operating on commercial modem hardware produced by Small Business Innovation Research (SBIR) contractor Benthos, Inc. Racom buoys are gateway nodes that have successfully incorporated line-of-sight FreeWave radios, cellular digital packet date (CDPD) telephone modems, Iridium satellite communications (SATCOM) modems, and Global Positioning System (GPS) receivers. Sublink capability has been implemented easily on WQC-2 and BSY-1 submarine sonar. A Seaweb server resides at manned command centers and is the interface to the undersea network.

The power of Seaweb connectivity was successfully and dramatically demonstrated during recent Navy and international experiments. Figure 2 is a chart of the Fleet Battle Experiment India (FBE-I) Seaweb network, a

14-node undersea grid. Two nodes were DADS multi-influence sensors; ten were telesonar repeaters; and two were moored Racom buoys. An improved 688-class fast-attack submarine with Sublink capability had full interoperability with the Seaweb network. Seaweb servers aboard the submarine and at the ashore ASW Command Center provided a graphical user interface and a portal for the DADS operator display. Seaweb traffic originated asynchronously at the two DADS nodes, at the submarine, and at the ASW Command Center, and the link-layer protocols automatically resolved network contentions whenever Seaweb transmissions collided. Test personnel exercised the complete Seaweb installation for 4 days with high reliability and no component failures.

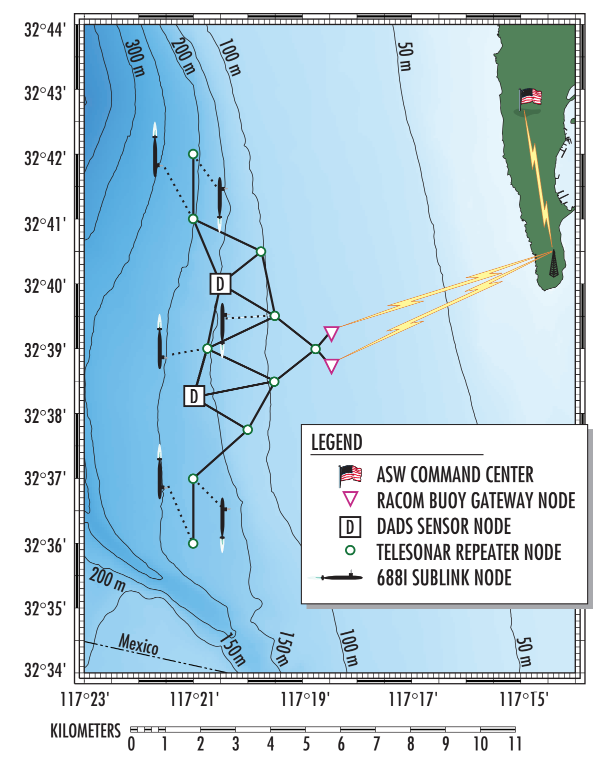

FIGURE 2. The June 2001 FBE-I Seaweb network was installed on the Loma Shelf adjacent to San Diego. The undersea wireless grid provided bi-directional cellular communications to a telesonar-equipped fast-attack submarine operating as a Seaweb mobile node, depicted in the figure at six different positions.

Figure 3 is a chart of the Seaweb network interconnecting Canadian and U.S. passive acoustic sensors during The Technical Cooperation Program (TTCP) RDS-4 experiment. Line segments indicate telesonar links, and bolts indicate FreeWave line-of-sight radio and Iridium satellite links. Without any prior integration effort, the Seaweb network readily assimilated the Canadian instruments upon installing Seaweb firmware in the commercial telesonar modems. RDS-4 culminated the Rapidly Deployable Sensors (RDS) program by the TTCP Sonar Technology Panel.

Figure 4 shows the Q272 Seaweb network deployed from Canada Forces Auxiliary Vessel (CFAV) *Quest* during a bilateral Canada/U.S. TTCP venture. One Canadian and two U.S. Navy Webb Research Corporation (WRC) AUV gliders served as mobile nodes in an undersea acoustic network for 7 continuous days, accumulating over 300 vehicle hours of operation. A seafloor grid of six Seaweb repeater nodes and two moored Racom gateway nodes supported communication and navigation for the submerged gliders. When surfaced, the gliders acted as mobile gateway nodes for the undersea network, interfacing telesonar with Iridium SATCOM, FreeWave line-of-sight, and GPS radios. The 200 kilometers logged by the AUV glider fleet provided unprecedented ocean observation of glider performance and afforded testing opportunities for glider-integrated acoustic sensors, towed acoustic sensors, and station keeping. The experiment demonstrated enabling technologies for glider cooperative behavior as an autonomous mobile fleet and in conjunction with fixed autonomous assets.

TRANSMISSION SECURITY

Telesonar signaling involves broadcasting energy into the undersea environment. The question arises as to what recourse is available to system designers and mission planners to conceal the use of such energy from an adversary? In a tactical situation, how can telesonar signaling be made immune to jamming and other countermeasures? How does one analyze the problem? Transmission security (TRANSEC) is the present emphasis of the discovery and invention projects within the Seaweb Initiative. Feedback from Navy commanders indicates that fleet acceptance of Seaweb-based systems critically depends on the incorporation of TRANSEC. Achieving TRANSEC as an integral feature of telesonar-based networking will foster the extension of Seaweb to clandestine missions and stealthy platforms, all of them interoperable with the aforementioned existing applications.

Compared with traditional point-to-point acoustic communications approaches, telesonar TRANSEC inherently derives from the relatively low transmit power levels and high frequencies made feasible by Seaweb network routing and repeater nodes. Telesonar link-budget analysis [16] is aiding the design of an evolving Seaweb physical layer incorporating electronically steered directional transducers [17], higher acoustic frequencies, increased spectral bandwidth, spread-spectrum signaling [18 and 19], and power control.

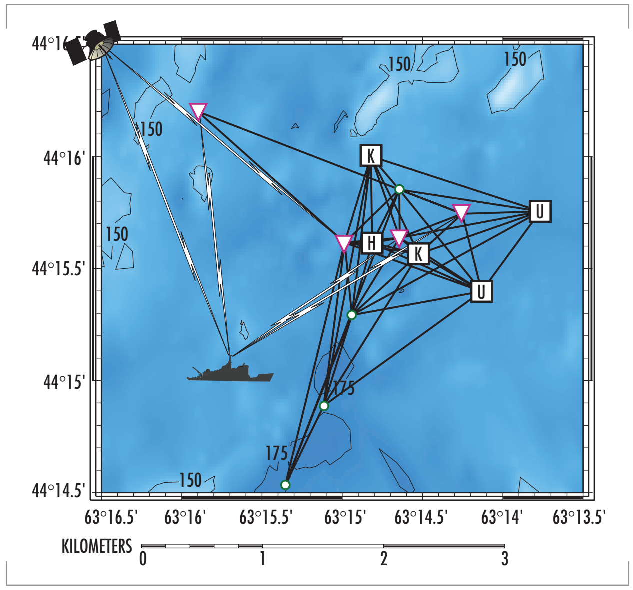

FIGURE 3. The October 2002 RDS-4 Seaweb network in the Approaches to Halifax supported the RDS-4 Rapidly Deployable Sensors Trials. Seaweb networking integrated U.S. and Canada experimental autonomous ASW sensors deployed on the seafloor. Gateway buoys supported FreeWave line-of-sight radio links and Iridium satelite links to the shipboard command center. Legend: ▽– U.S. and Canada gateway buoys; H – U.S. Hydra HLA sensor; K – U.S. Kelp VLA sensors; U – Canada UCARA HLA sensors; ○ – U.S. Seaweb repeater nodes.

CONCLUSION

Undersea, off-board, autonomous systems will enhance the war-fighting effectiveness of submarines, maritime patrol aircraft, amphibious forces, battle groups, and space satellites. Wide-area sensor grids, leave-behind multi-static sonar sources, mine-hunting robots, and AUVs are just a few of the battery-powered, deployable devices that will augment space and naval platforms. Distributed system architectures offer maximum flexibility for addressing the wide array of ocean environments and military missions. Transformation of undersea warfare will result from the ability of mission planners and theater commanders to deploy an appropriate mix of undersea sensors, vehicles, and other devices from a repertoire of evolving component systems. Sea power is achieved through the ability to match a resource set to the ocean environment and the mission at hand. Robust, environmentally adaptive telesonar modems interconnect undersea assets,

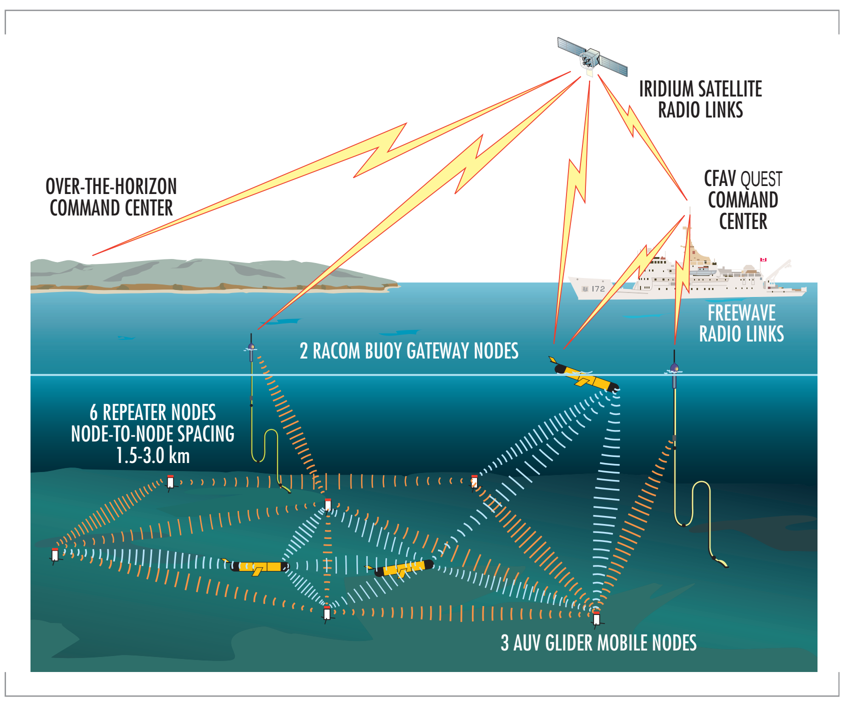

FIGURE 4. The February 2003 Q272 Seaweb network in the Eastern Gulf of Mexico included three AUVs, six repeater nodes, and two gateway buoys. The experiment exercised Seaweb ranging functions for tracking and navigating mobile nodes. The AUVs proved themselves as effective mobile gateway nodes with telesonar, FreeWave, Iridium, ARGOS, and GPS.

integrating ad hoc deployments into a unified Seaweb. Network interfaces to manned command centers via gateways such as those provided by Sublink and Racom are essential components. The sensor-rich fixed grid benefits from visits by AUVs for the high-bit-rate data uploads and intel downloads. AUVs and submarines use the fixed grid for networked command, control, communications, and navigation. For amphibious operations, deployed meteorological and oceanographic (METOC) systems inform the battle group, and in situ ASW sensing seamlessly gives way to in-stride autonomous mine countermeasures in support of the approaching force. Seaweb provides the necessary infrastructure for common situational awareness and collective adaptation to the evolving basic rhythm and rules of engagement.

Seaweb revolutionizes naval warfare by ultimately extending network-centric operations into the undersea battlespace. In a letter dated 27 March 2002, ADM(Ret) James R. Hogg, Director of CNO's Strategic Studies Group, states, "Seaweb was quite valuable in conceiving the seabed-to-space multi-tiered sensor field of ForceNet. This work demonstrates an excellent model for an underwater sensor field and wireless network, and helped answer some of the challenges of networking in such a difficult medium."

ACKNOWLEDGMENT

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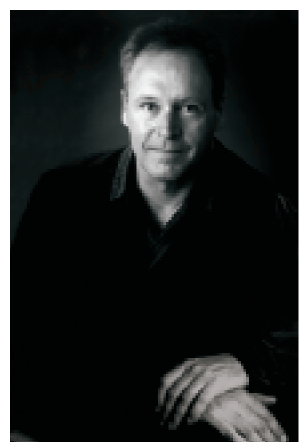

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Deployable Autonomous Distributed System: Future Naval Capability in Undersea Warfare

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ABSTRACT

Naval forces operating in the littoral must achieve and maintain undersea battlespace superiority, overcoming area-denial efforts by the adversary. One of the most lethal area-denial platforms is the modern diesel-electric submarine. The objective of the Deployable Autonomous Distributed System (DADS) project is to improve the Navy's capability to conduct effective antisubmarine warfare (ASW) and intelligence, surveillance, and reconnaissance (ISR) operations in the littoral. This improvement will reside primarily in areas of rapid response, reduced system vulnerability, and reduced systems cost and operator workload. DADS is the primary focus of the Navy's advanced development in wide-area surveillance, sponsored by the Office of Naval Research under the Littoral ASW Future Naval Capabilities program.

INTRODUCTION

Forward-area dominance has become a critical element of our national defense strategy and of naval operations. The vision of Sea Power 21, consisting of the components of Sea Strike, Sea Shield, and Sea Basing, was developed to support this naval strategy, and the term FORCEnet is used to describe the architecture that connects these components together, integrating existing networks, sensors, and command and control systems.

The Deployable Autonomous Distributed System (DADS) program was established by the Office of Naval Research to contribute to Sea Strike and Sea Shield through its unique capability to provide a quick response to the need for wide-area undersea surveillance in the littoral. DADS is being developed as an undersea antisubmarine-warfare (ASW) sensors component of FORCEnet. To achieve this unique capability, the DADS program is pursuing technology development in several areas. These enabling technologies are miniature low-power and low-cost acoustic and electromagnetic sensors; automated surveillance contact report generation in a self-contained undersea processing module; network control and data fusion; and transmission of the information back to a tactical command center via acoustic and radio-frequency (RF) data links [1]. Figure 1 illustrates the DADS concept of operations.

The DADS program is currently conducting system feasibility demonstrations of sensor nodes, automated contact reporting, and communication links. This paper will describe the technology development effort supporting these demonstrations with a focus on one of the more challenging components—automated contact classification.

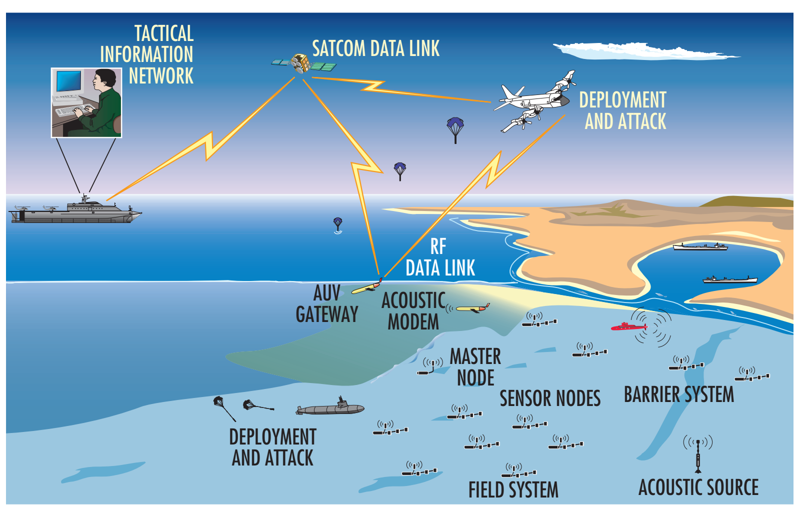

FIGURE 1. Deployable Autonomous Distributed System concept of operations.

DADS TECHNOLOGY

DADS consists of three major components: sensor nodes, communication gateways, and a control terminal. Sensor nodes consist of a 100-meter array containing 28 hydrophones and 3 magnetometers, a communication module consisting of an undersea acoustic modem and transducer, and an electronics module containing processing electronics and battery. Figure 2 is a drawing of the DADS sensor node components.

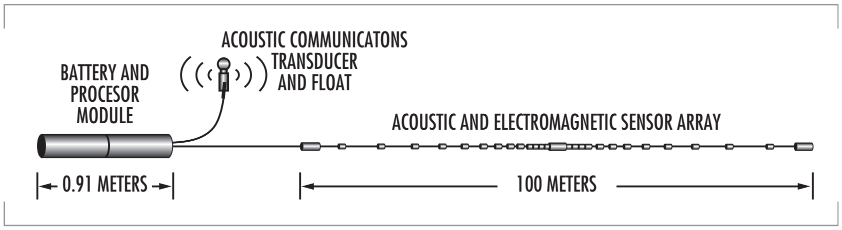

FIGURE 2. DADS sensor-node components.

Communication gateways can either be moored buoys or mobile autonomous undersea vehicles. Both moored and mobile gateways contain acoustic and RF modems and associated transducers and antennas. DADS sensors and gateways, as deployed in the ocean, are shown in Figure 3.

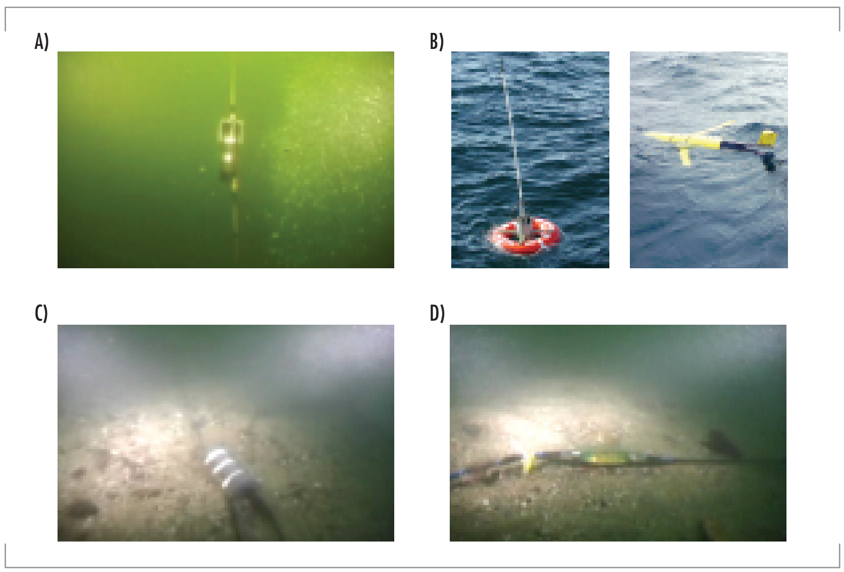

FIGURE 3. DADS (A) acoustic modem, (B) moored and mobile gateways, (C) magnetometer, and (D) hydrophone.

The control terminal is located in the ASW Control Center and consists of a laptop computer and RF communications electronics. The computer provides control of the sensor nodes and gateways and also displays the current status of the system and contact report information. An important element of the DADS is automated target recognition and contact reporting. The objective is to distinguish submarines from surface ships and report their presence [2].

To provide a robust detection, classification, and localization capability in the littoral, a combination of acoustic and electromagnetic sensors and associated signal-processing algorithms are used. Major signal-processing components in the sensor node include detection, tracking, track association, feature extraction, contact classification, and contact reporting [3].

To meet system-lifetime objectives, it is important to minimize the flow of contact report data among sensor nodes in the DADS network. Therefore, it is desirable to do as much contact classification in the sensor node as possible. In the DADS concept, the initial classification processing in the sensor node uses two sources of information to distinguish a contact of interest from all other contacts:

1. *Magnetic Matched-Field Tracking (MMFT) Features*—The MMFT process uses magnetometer data to generate a three-dimensional track for the contact. This track, therefore, defines the contact depth, along with the track dynamics. The MMFT process also estimates the contact’s magnetic moment. These features are used as

positive surface/subsurface discriminators. A positive discriminator is one that provides indications that the contact is subsurface and therefore a possible target of interest [4].

2. *Acoustic Features*—Hydrophone data are analyzed to generate acoustic features for all contacts. These features include broadband signature information, narrowband tonals, harmonic relationships, and all the attributes of these detected signals (such as signal-to-noise ratio [SNR], frequency, bandwidth, etc.). Acoustic features are used as negative discriminators to indicate a contact is on the surface.

Magnetic Matched-Field Tracking

Automated electromagnetic signal processing begins with the application of matched-filter detection algorithms to ultra-low frequency (ULF) magnetic field data. A matched-filter process examines the ULF data for the presence of a quasi-static signature produced by the moving steel hull of surface ships and submarines. When the ULF detector threshold is exceeded, localization and track processing using MMFT algorithms are initiated.

MMFT analysis requires measurement of the vector components of the magnetic field at spatially separate points. For the DADS sensor array, vector fields are measured at three points with 50-meter spacing. This measurement is accomplished by using magnetometers whose location and orientation in the earth's magnetic field are known. Epochs lasting 40 seconds with a 50-percent overlap are processed sequentially over a period of several minutes to develop a complete track. For each epoch, a beginning and an ending location is assumed for a constant velocity and depth track from a point dipole source. A "replica" field that would result at each magnetometer location due to the movement of a magnetic dipole along this trajectory is calculated. This calculation is accomplished by determining three dipole moment components (Mx, My, Mz) that produce the best match between the replica and data. The procedure of adjusting the hypothesized track and determining magnitude and direction of the best-fit dipole is repeated until the correlation between the replica and the data cannot be improved. The magnetic-field replica equation is given in Eq. (1).

$$\begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} = \left(\frac{\mu_0}{4\pi} r^{-5} \right) \begin{bmatrix} 3x^2 - r^2 & 3xy & 3zx \\ 3xy & 3y^2 - r^2 & 3yz \\ 3zx & 3yz & 3z^2 - r^2 \end{bmatrix} \bullet \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} \tag{1}$$

where B_x, B_y, and B_z are magnetic flux density (Tesla), m_x, m_y, and m_z are dipole moment components (ampere • meter^2), μ_0 is permeability ($4\pi \times 10^{-7}$ Henrys/meter), and $r = \sqrt{x^2 + y^2 + z^2}$ (meters).

An important feature of this process is that target depth, speed, range, bearing, and magnetic moments are obtained in near real time. Depth, speed, and range are used to support target tracking, and depth and magnetic moment support classification.

Acoustic Tracking and Track Association

Automated acoustic tracking is accomplished by using established narrowband and broadband acoustic signal-analysis methods. The analysis consists of applying spectral estimation, noncoherent integration, noise mean estimation, and signal clustering to the correlated output from a split-aperture adaptive beamforming process. The objective is to generate signal clusters in bearing and frequency space. Tracking is accomplished by association of clusters, in bearing and frequency space (narrowband) or bearing only (broadband), over time (Figure 4). An α–β tracker is used to associate the acoustic clusters to the magnetic track to form a contact track [5].

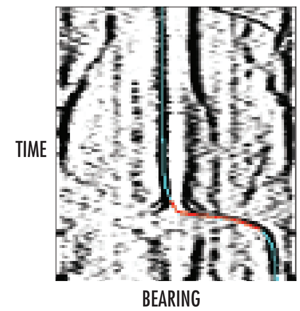

FIGURE 4. Association of acoustic (blue) and magnetic track (red) in time and bearing.

Contact Classification

Contact tracks, generated by the acoustic and magnetic track association process, include contact data structures that are the input to the classification process. These data structures consist of the magnetic and acoustic feature sets listed below.

1. Magnetic (MA): defines specific magnetic features such as magnetic moment, depth, and magnetic score. Membership functions are used to provide the scoring criteria.
2. Number of Blade Harmonics (NBH): defines a blade harmonic structure and provides membership functions for evaluating the number of blade harmonics.
3. Blade Harmonic Power (BHP): provides a membership function for evaluating the range normalized average power in each blade harmonic.
4. Non-Blade Power (NBP): provides a membership function for evaluating the range normalized average power in each non-blade narrow-band signal.
5. Contact Bearing Rate (CBR): provides a membership function for evaluating the contact bearing rate.
6. Number of Signal Events (NSE): provides a membership function for evaluating the number of associated signal events in each contact track.

A discriminant score for each contact is calculated using these features and associated membership functions [6]. The membership functions provide estimates of the probability of existence of each of the features. The contact discriminant scoring function is shown below in Eq. (2)

$$DS = DS_{MA} + DS_{NBH} + DS_{BHP} + DS_{NBP} + DS_{CBR} + DS_{NSE} \quad (2)$$

where DS is the discriminant score (ranges from –1 to +1), DS_{MA} is the magnetic discriminant score, DS_{NBH} is the number of blade harmonics discriminant score, DS_{BHP} is the blade harmonics power discriminant score, DS_{NBP} is the non-blade harmonics power discriminant score, DS_{CBR} is the contact bearing rate discriminant score, and DS_{NSE} is the number of signal events discriminant score.

Contact Scoring

The decision to transmit a contact report to the command center is based on the contact score. The contact score is calculated and updated from one processing interval to the next by using a discriminant function classifier. The algorithm used by the classifier is given below in Eq. (3).

$$TS(i) = TS(i-1) + K[DS(i) - TS(i-1)] \quad (3)$$

where TS is the target score (ranges from –1 to +1), K is the smoothing constant (ranges from 0.2 to 0.8), and DS is the discriminant score (ranges from –1 to +1). The target score is computed with a first-order recursion.

The smoothing constant is a parameter chosen to minimize variation between processing intervals due to noisy measurements.

SUMMARY

DADS is currently being tested in shallow-water areas to evaluate performance of the automated contact classification algorithms. These tests are being supported by exploratory development hardware consisting of four sensor nodes and two gateway buoys. In 2004, an advanced development model will be built consisting of 15 sensor nodes and 2 gateway buoys. This system, configured as a surveillance barrier, will be tested at sea in 2005. Analysis and evaluation of results will be conducted in 2006. Transition to acquisition is planned following successful completion of the surveillance barrier demonstration. Figure 5 depicts a DADS sensor node model, configured for air deployment.

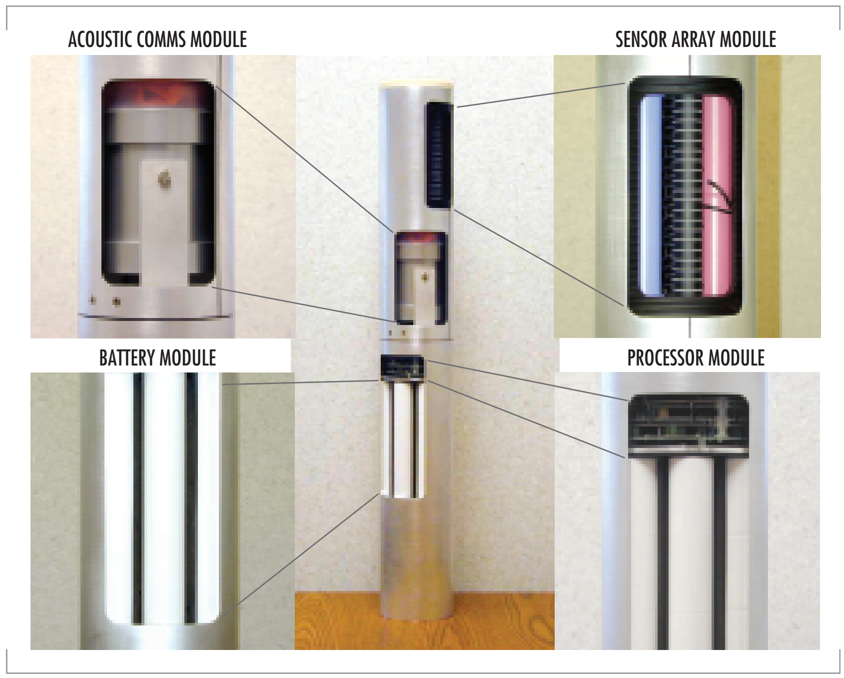

FIGURE 5. DADS "A-size" sensor node model.

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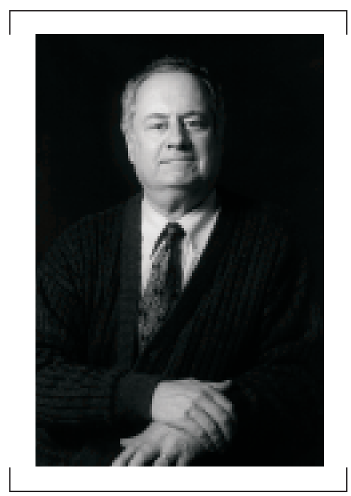

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